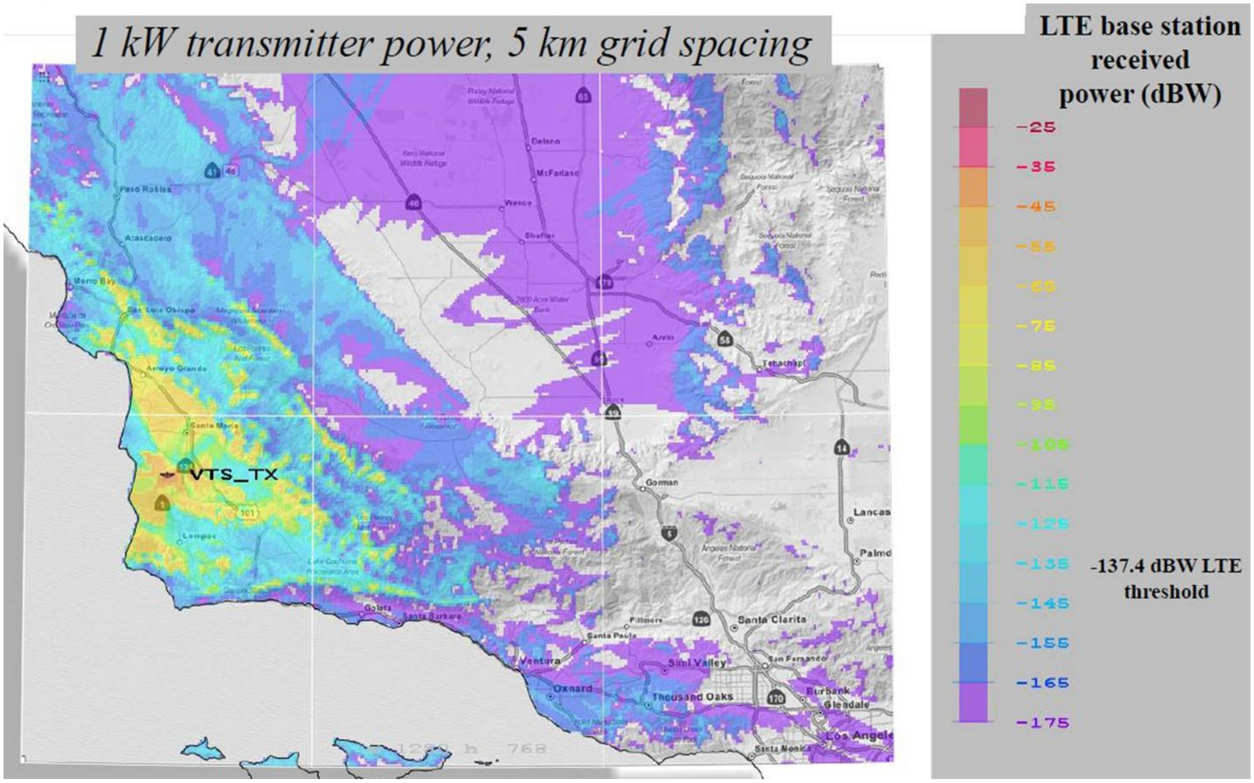


Figure 4.2.4-18 VTS Power Contours

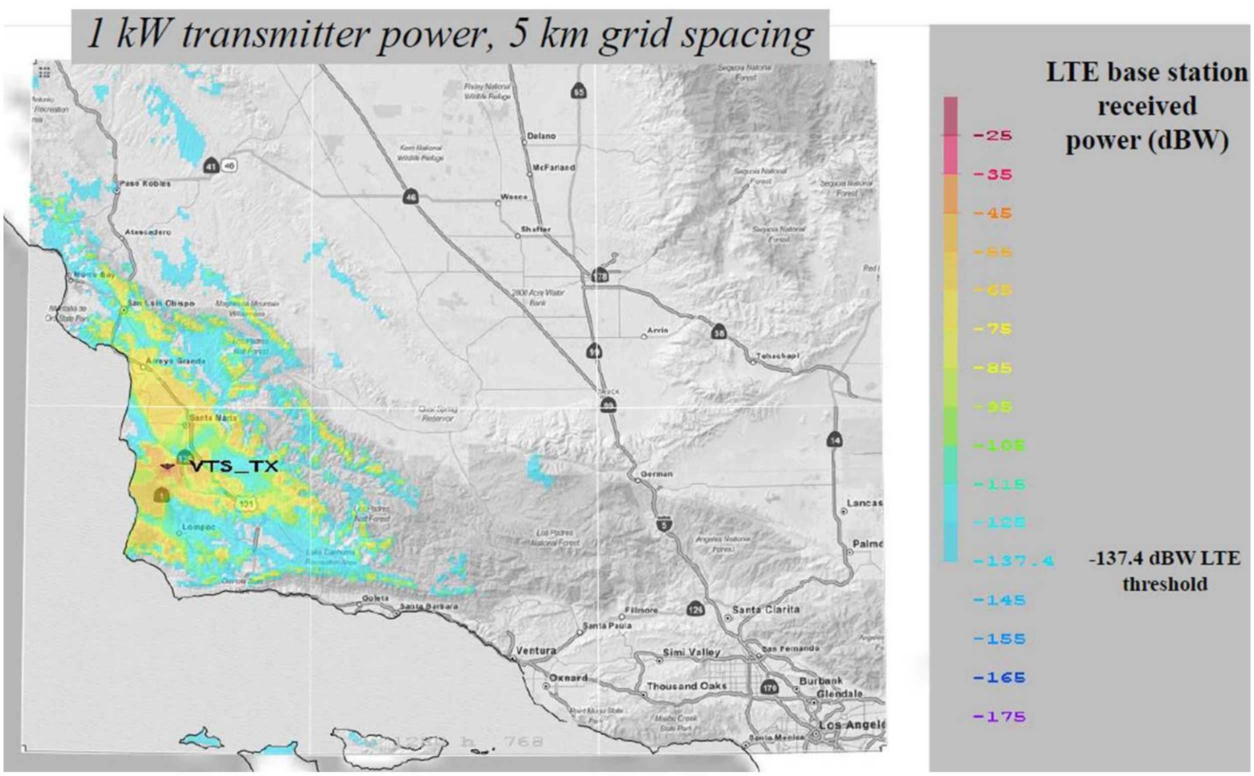


Figure 4.2.4-19 VTS Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

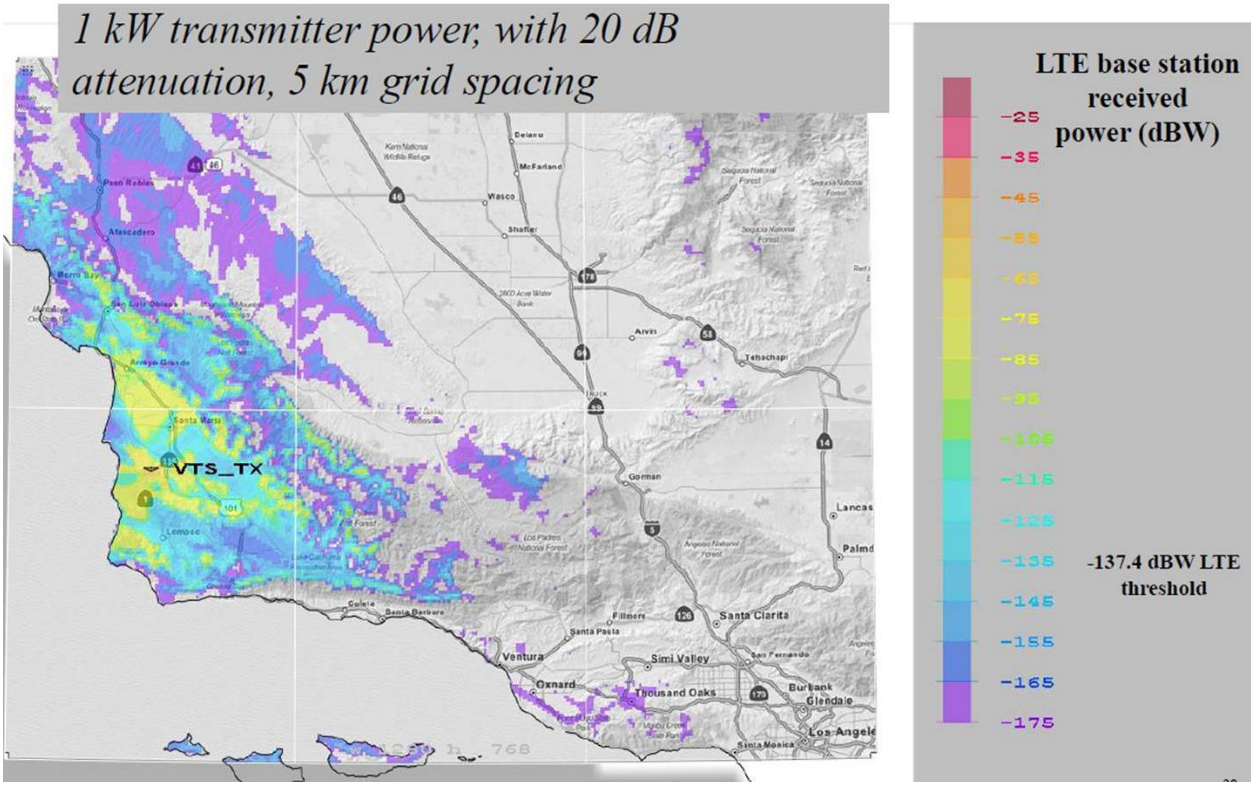


Figure 4.2.4-20 VTS Power Contours

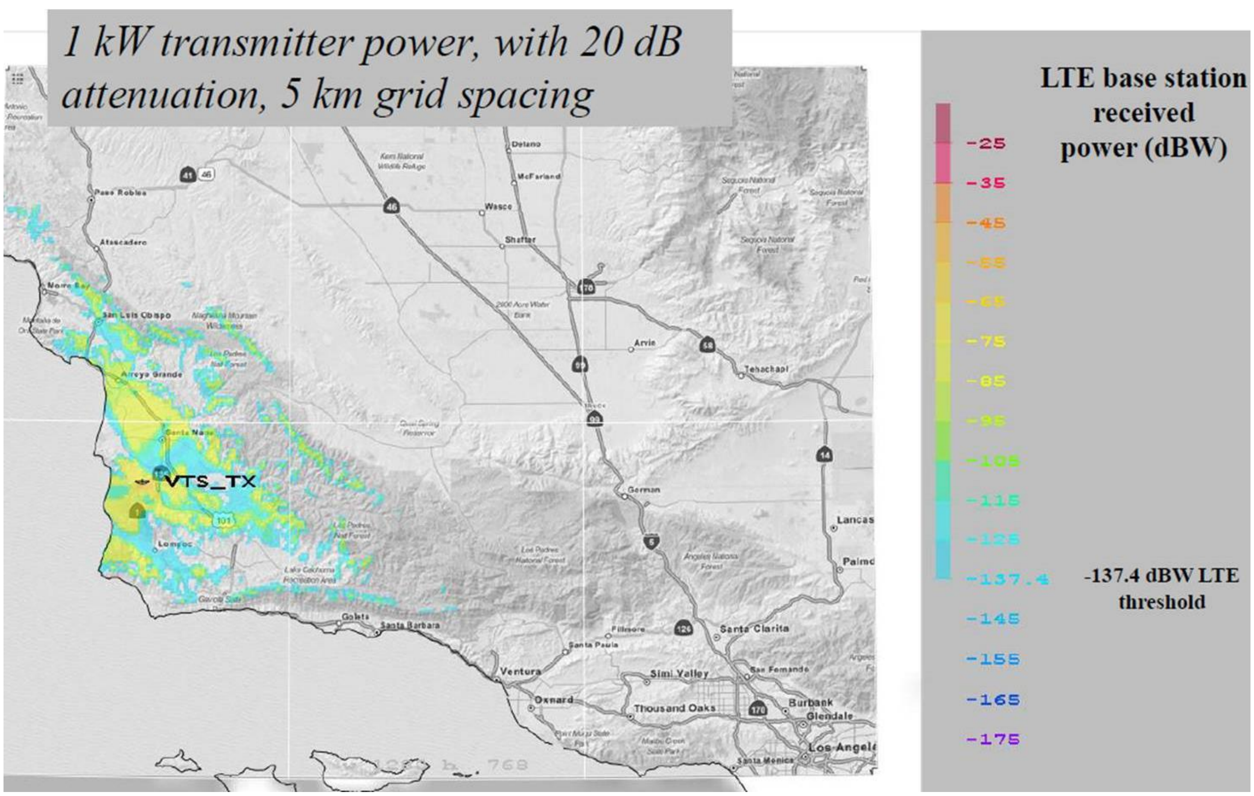


Figure 4.2.4-21 VTS Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

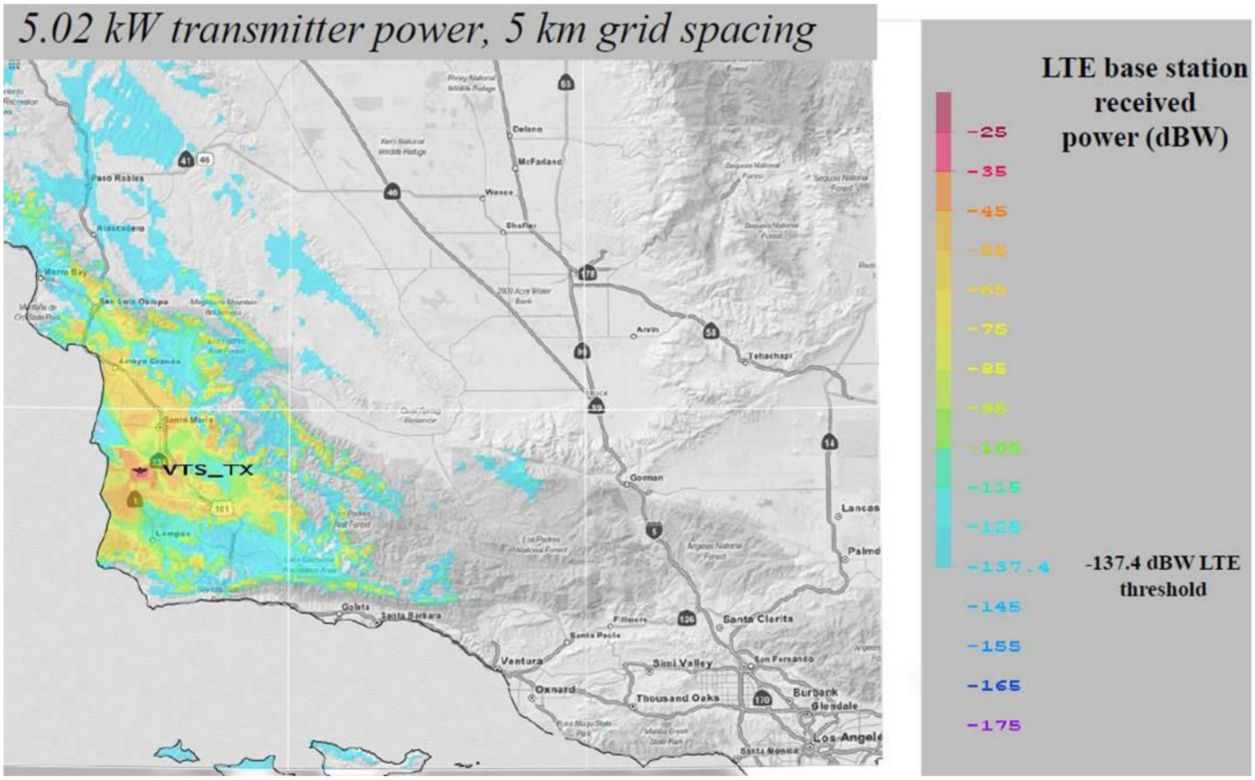


Figure 4.2.4-22 VTS Radiated Power (37.05 dBW, max power example)

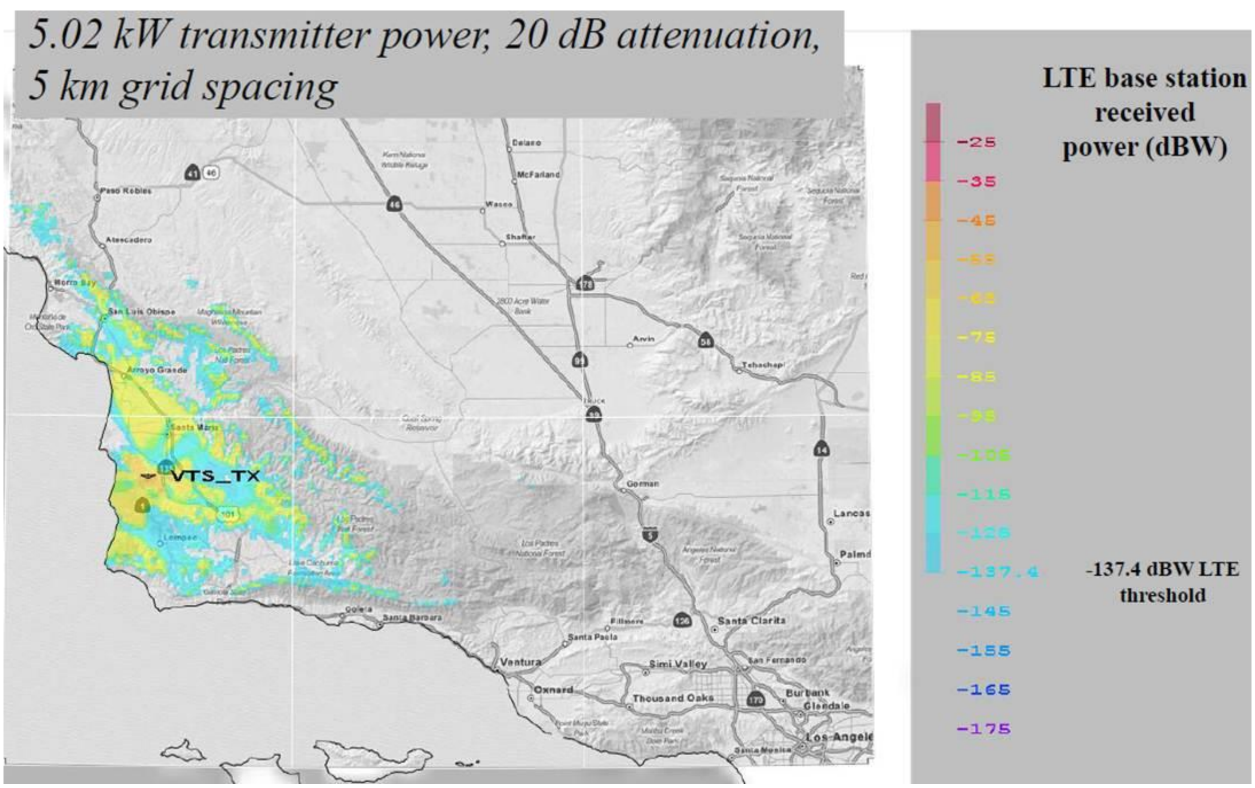


Figure 4.2.4-23 VTS Radiated Power (17.05 dBW, max power with attenuation)

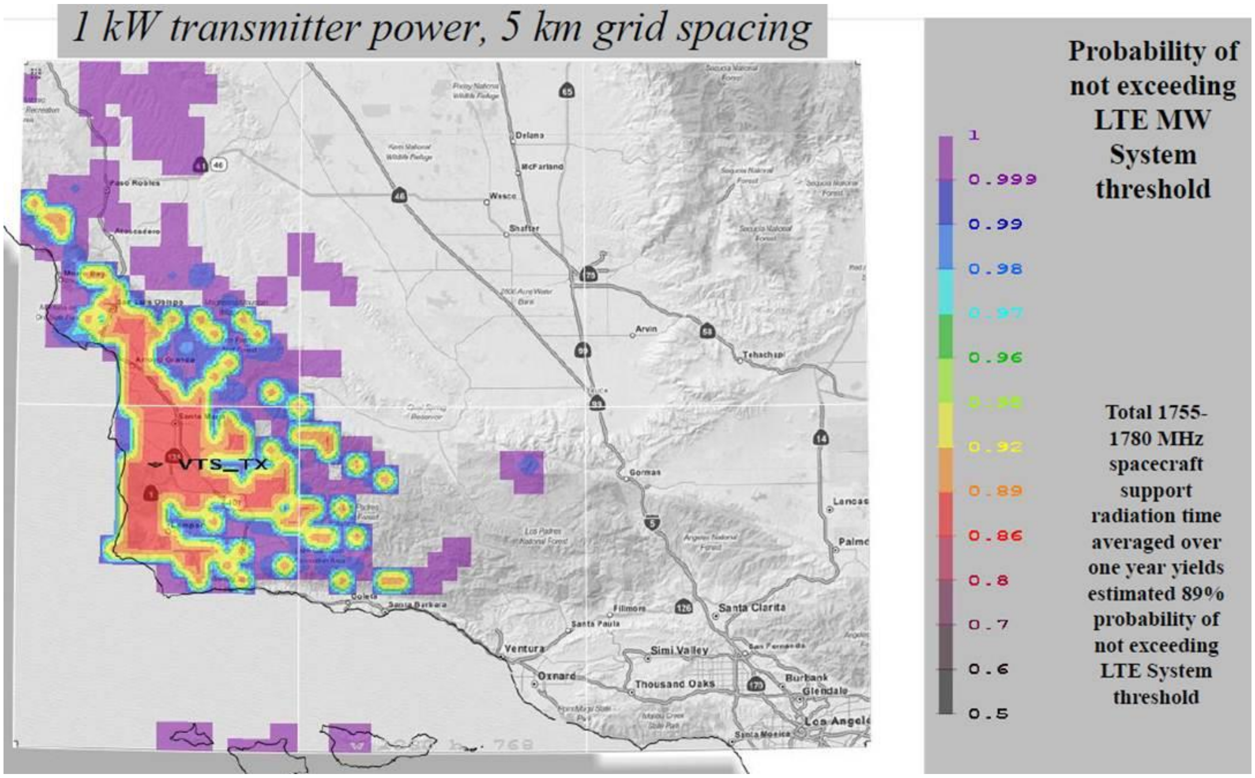


Figure 4.2.4-24 VTS LTE System Threshold Exceedance, 1755-1780 MHz

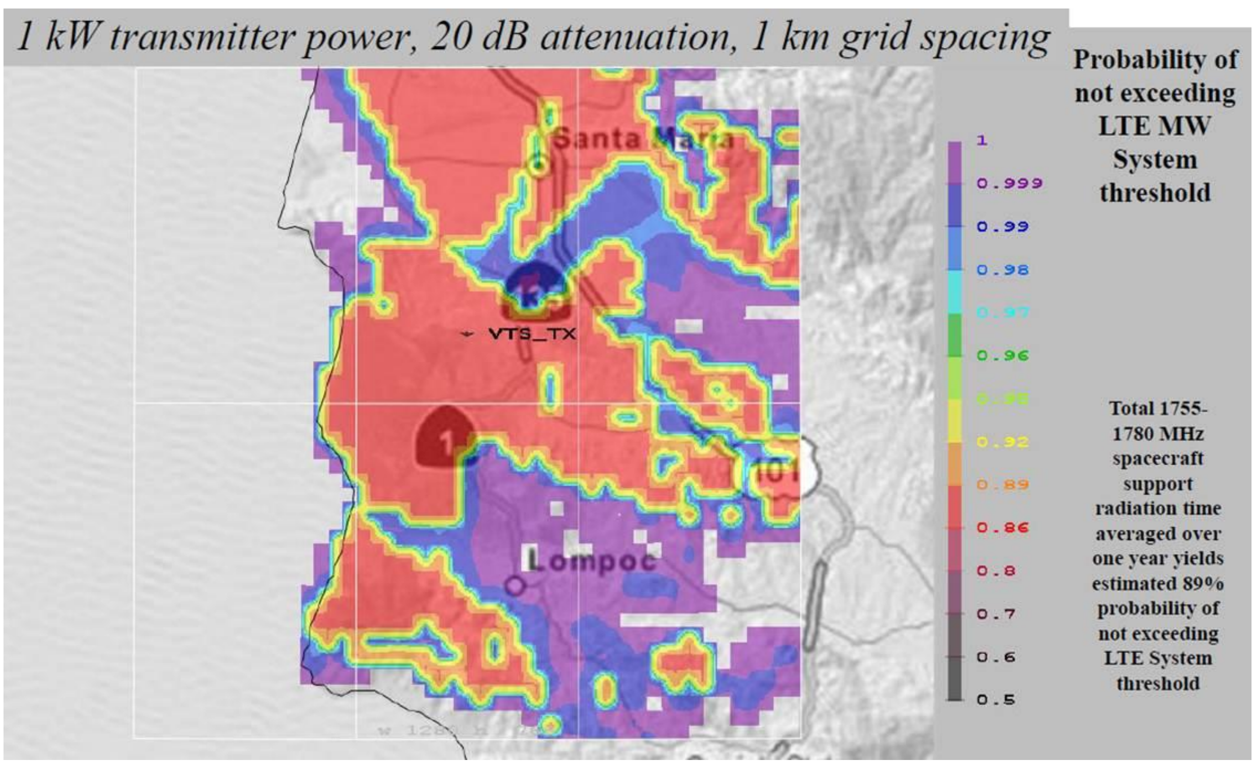


Figure 4.2.4-25 VTS LTE System Threshold Exceedance, 1755-1780 MHz

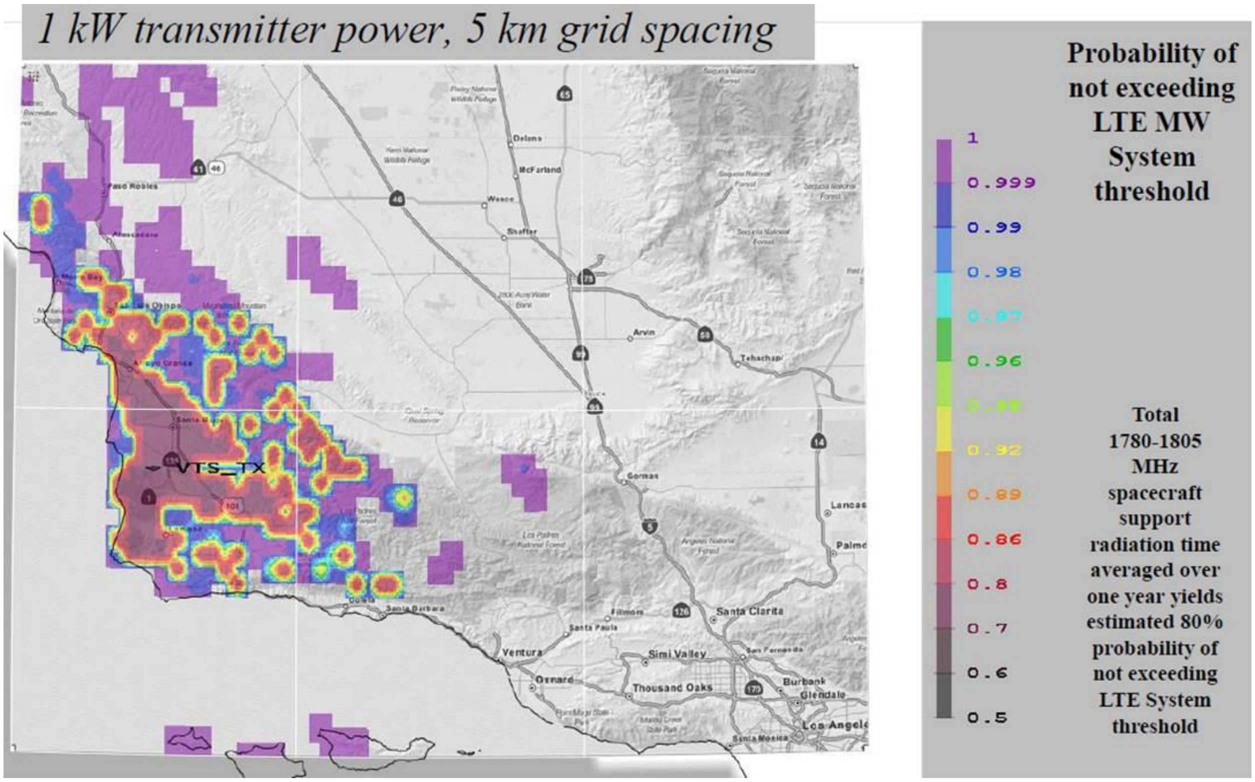


Figure 4.2.4-26 VTS LTE System Threshold Exceedance, 1780-1805 MHz

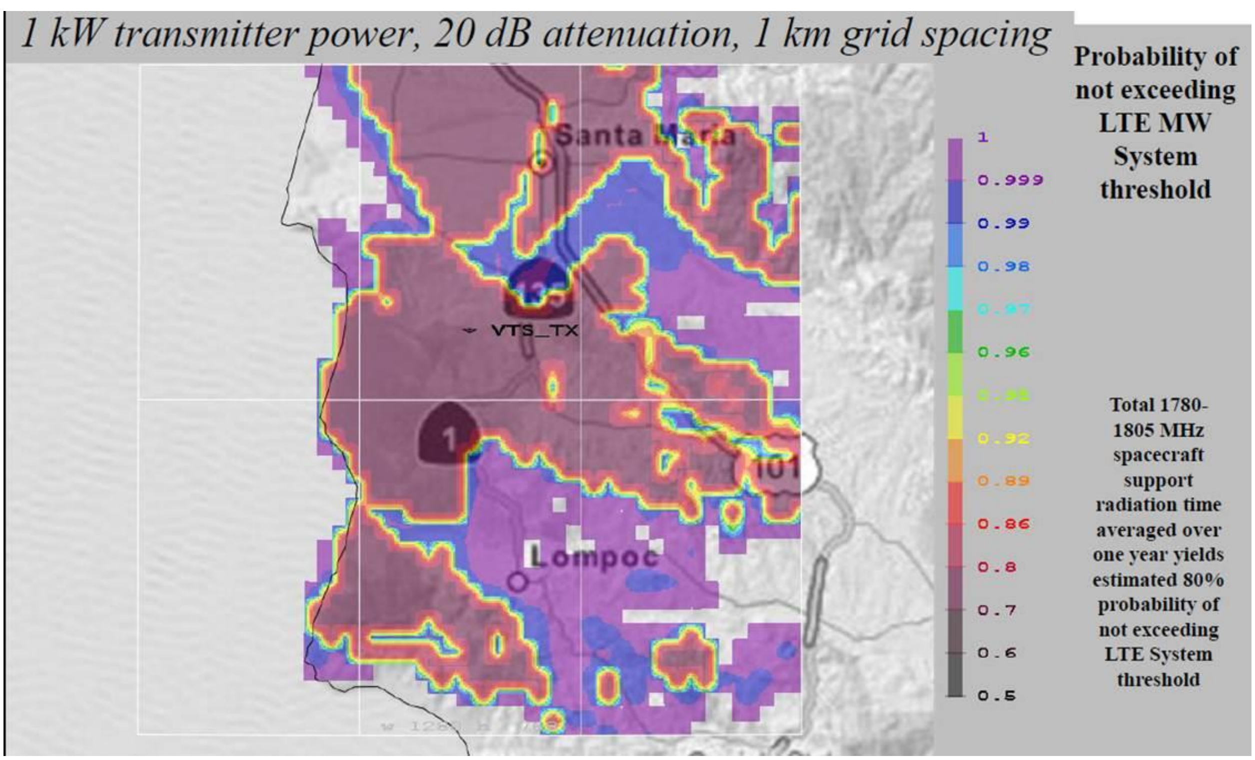


Figure 4.2.4-27 VTS LTE System Threshold Exceedance, 1780-1805 MHz

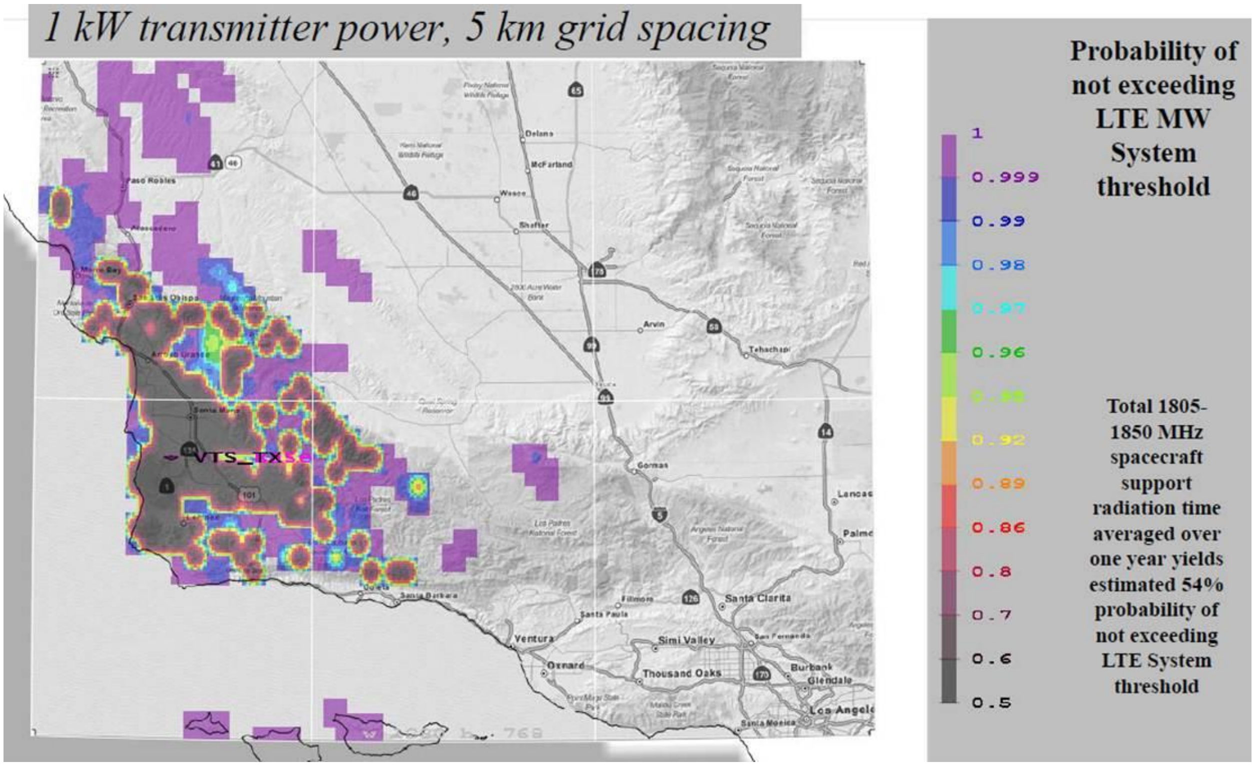


Figure 4.2.4-28 VTS LTE System Threshold Exceedance, 1805-1850 MHz

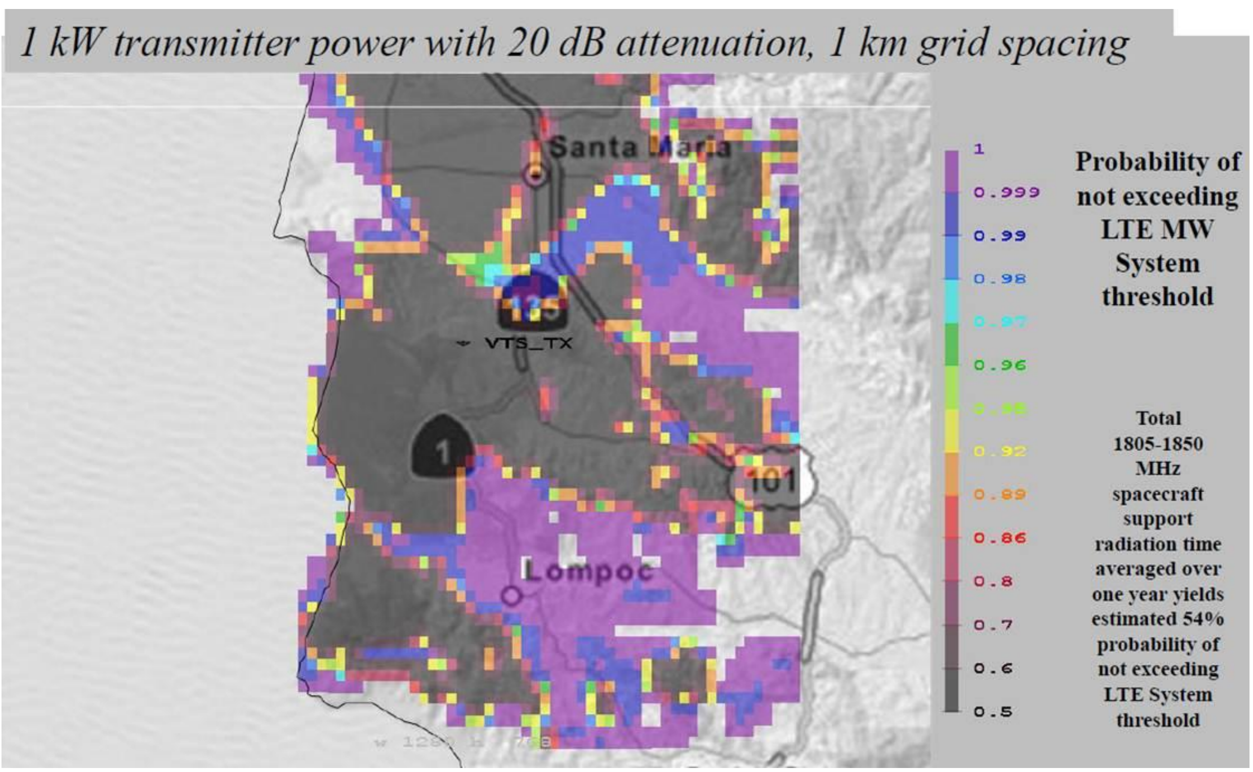


Figure 4.2.4-29 VTS LTE System Threshold Exceedance, 1805-1850 MHz

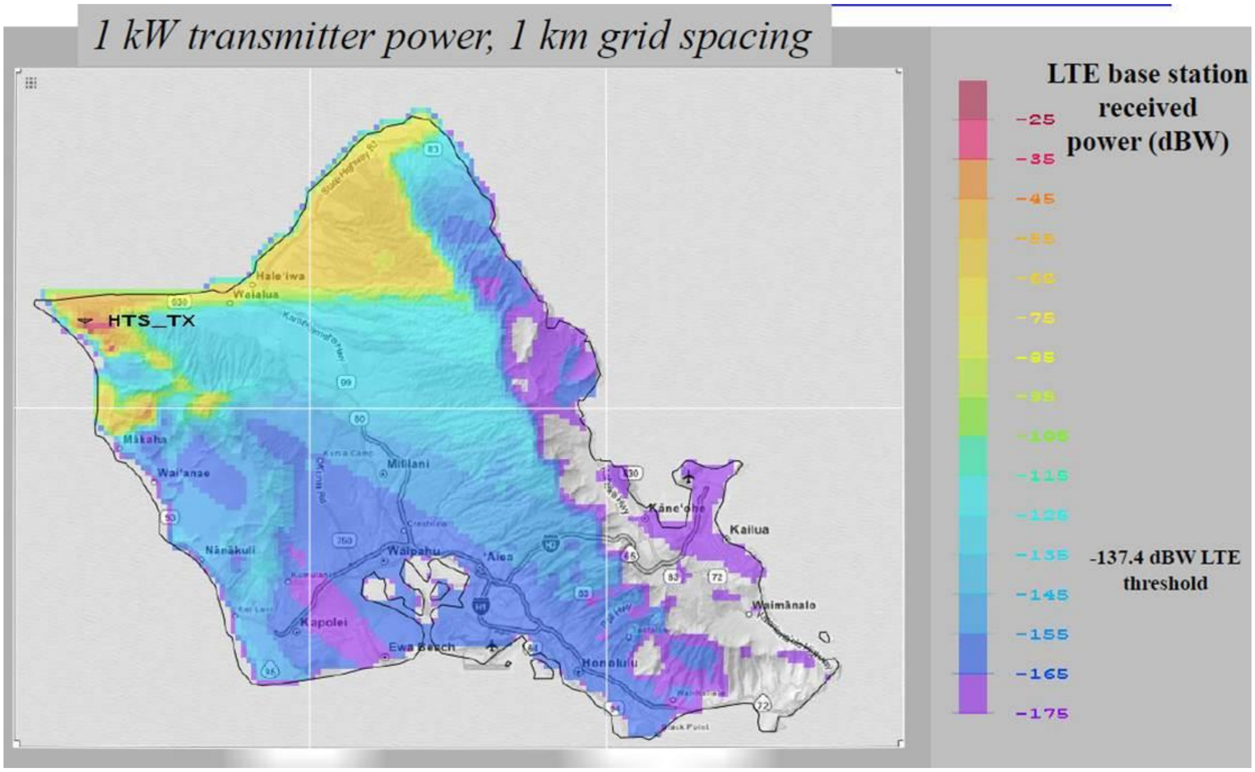


Figure 4.2.4-30 HTS Power Contours

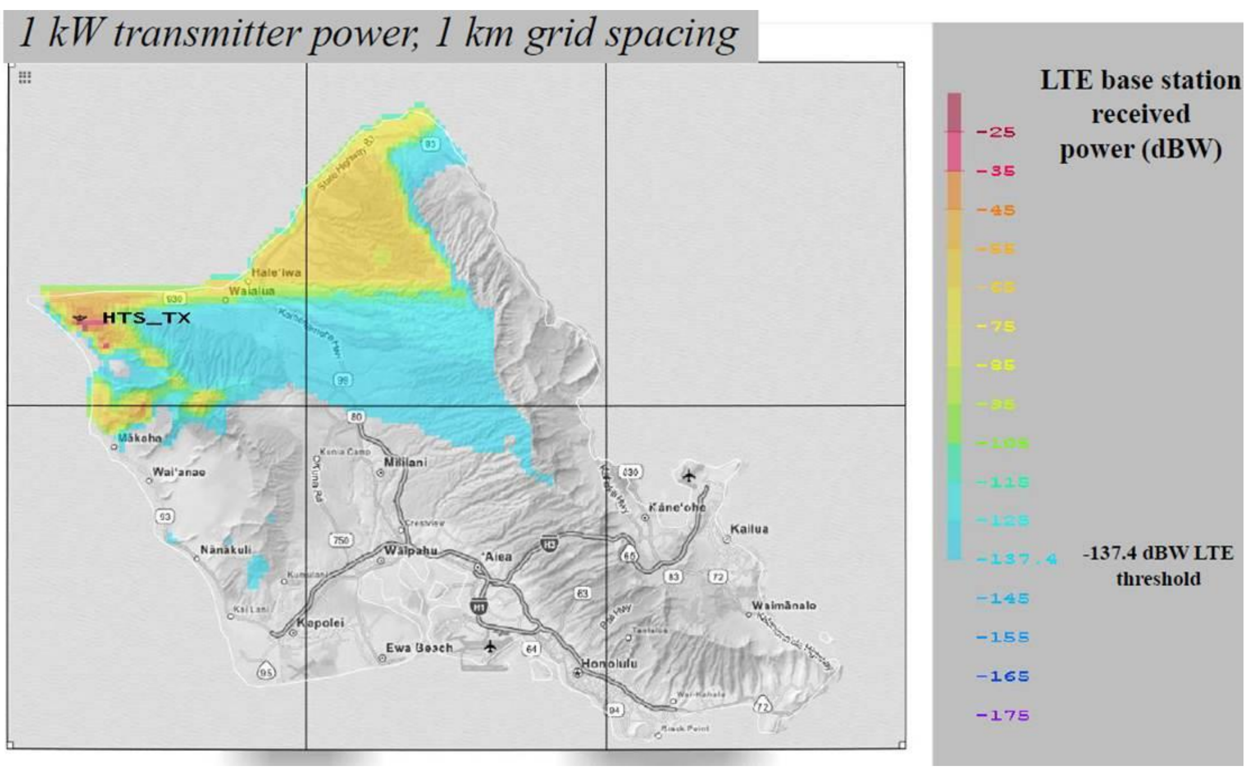


Figure 4.2.4-31 HTS Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

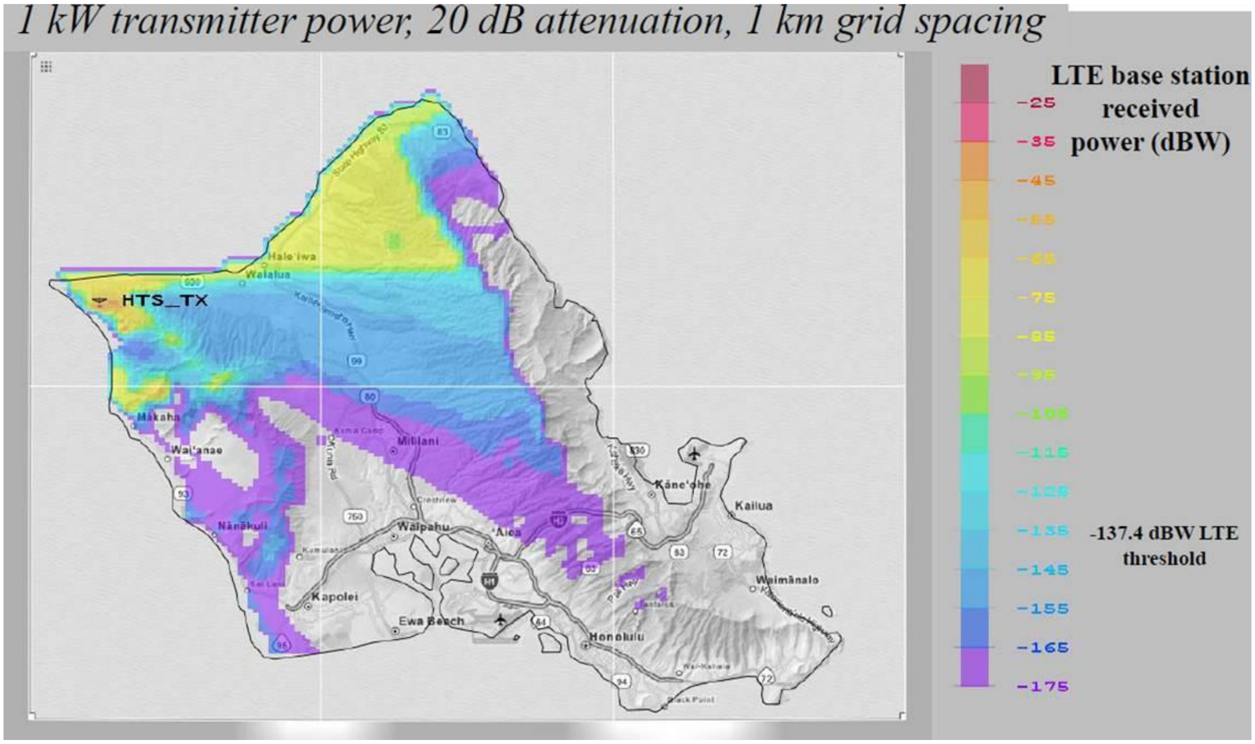


Figure 4.2.4-32 HTS Power Contours

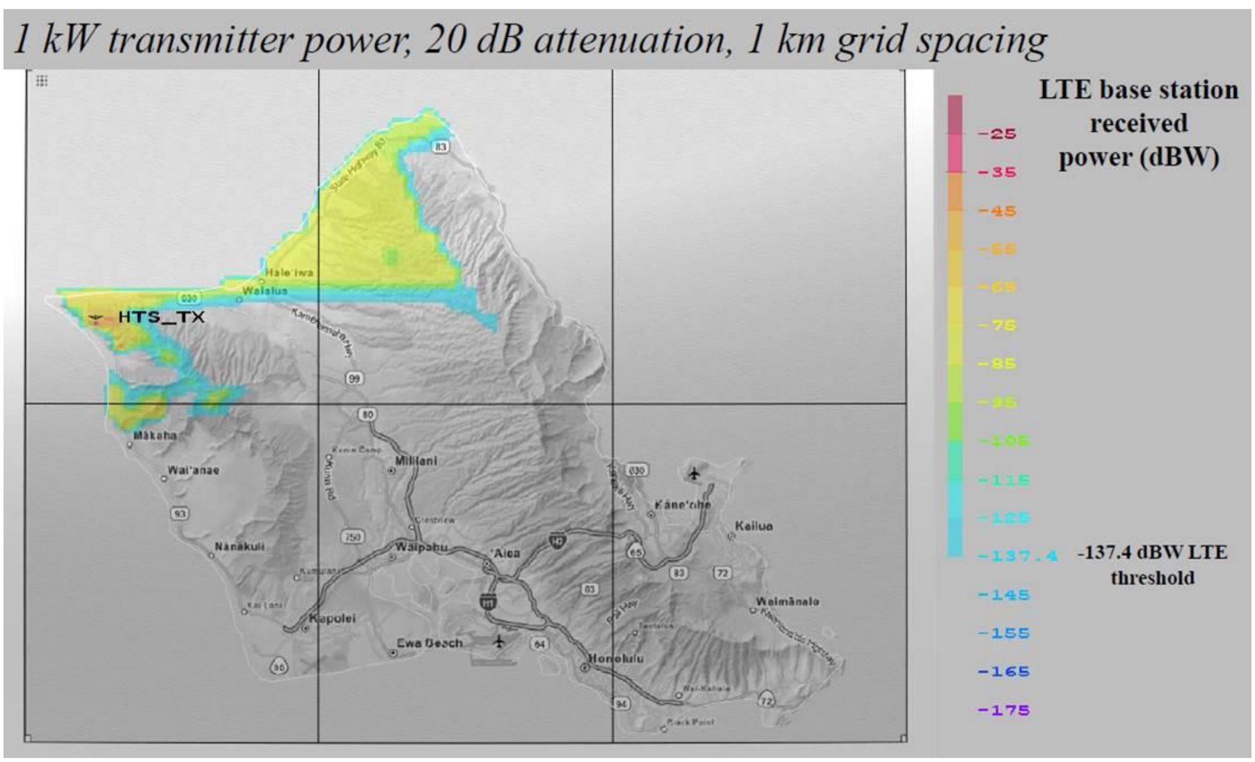


Figure 4.2.4-33 HTS Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

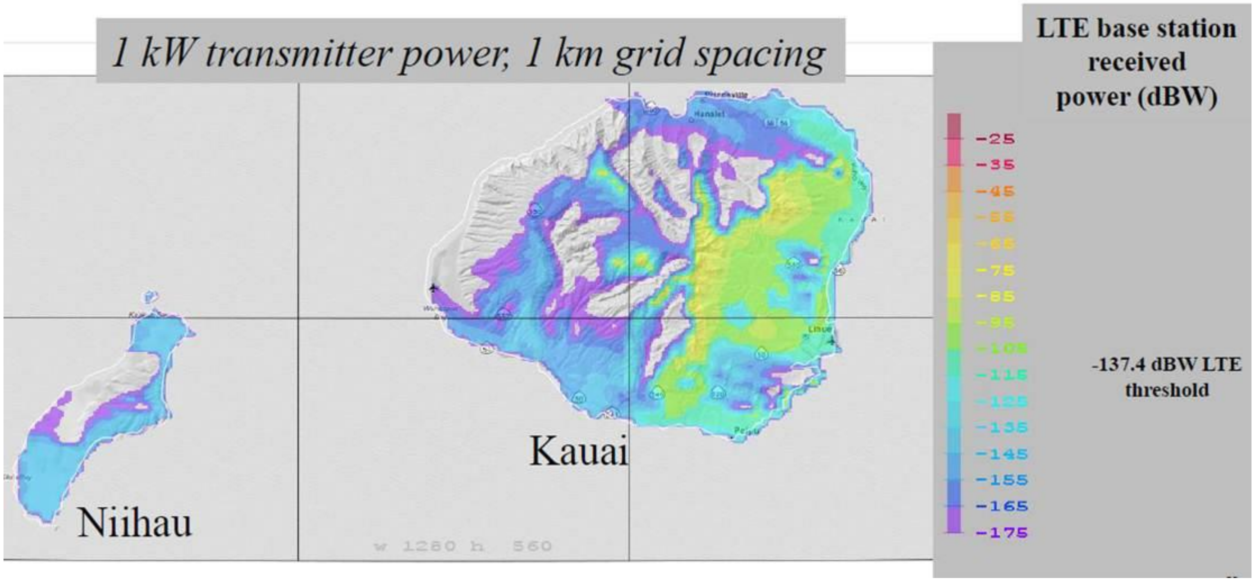


Figure 4.2.4-34 HTS Power Contours

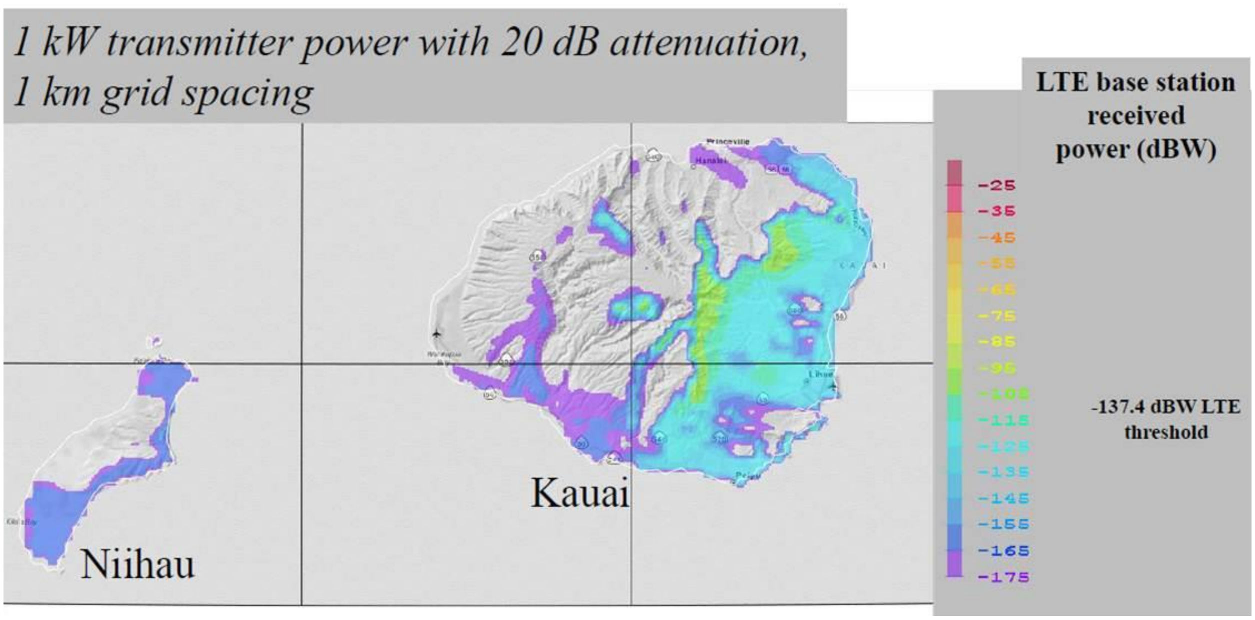


Figure 4.2.4-35 HTS Power Contours

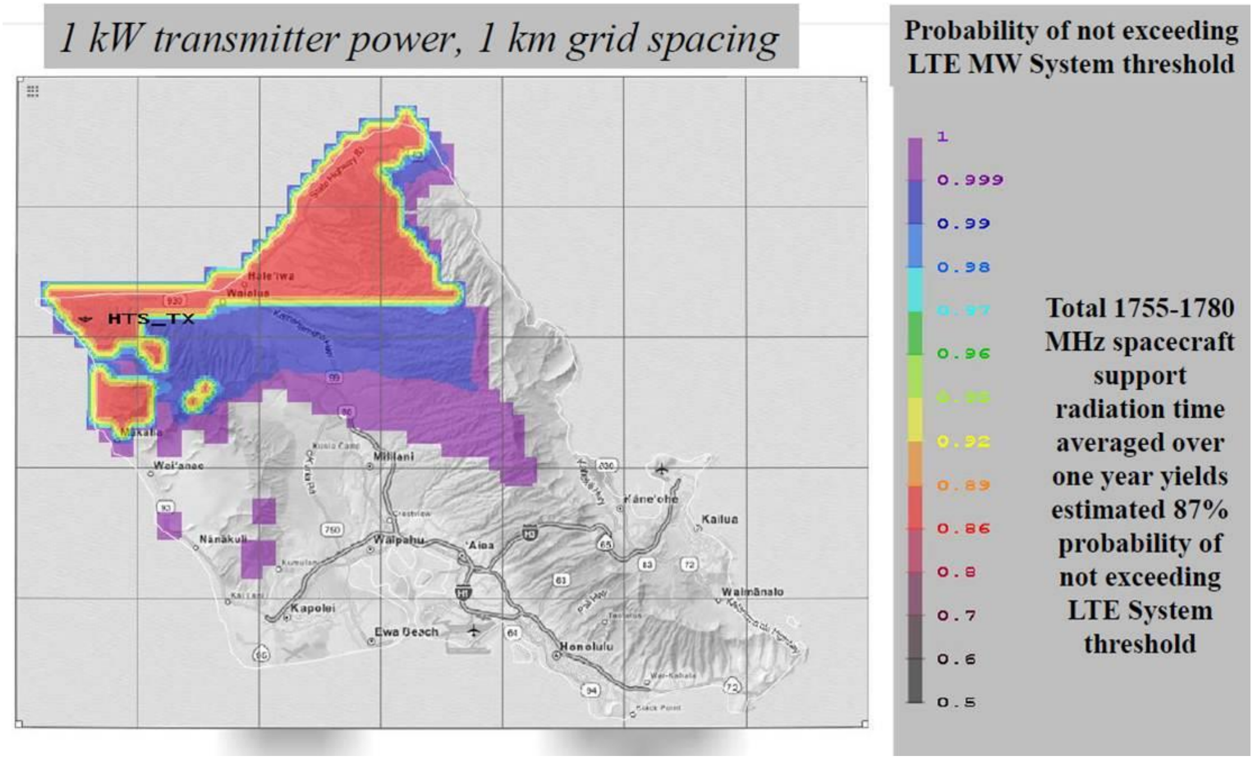


Figure 4.2.4-36 HTS LTE System Threshold Exceedance, 1755-1780 MHz

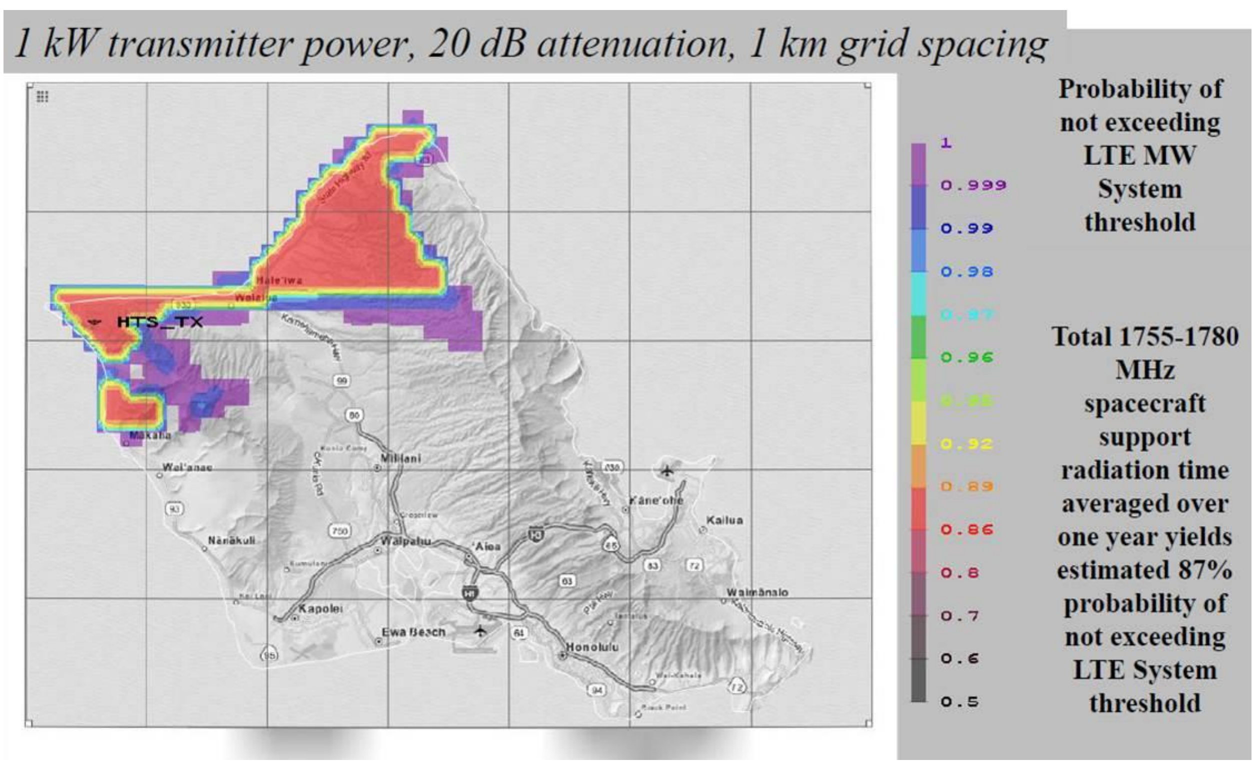


Figure 4.2.4-37 HTS LTE System Threshold Exceedance, 1755-1780 MHz

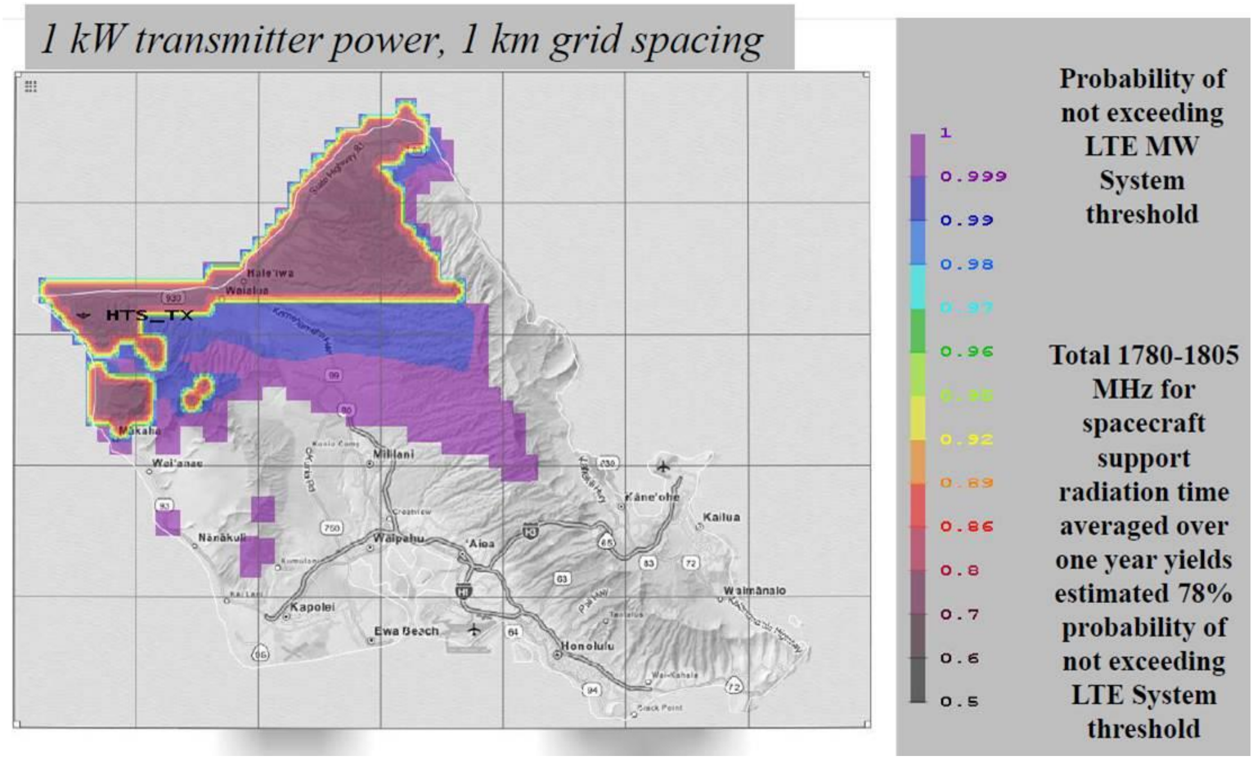


Figure 4.2.4-38 HTS LTE System Threshold Exceedance, 1780-1805 MHz

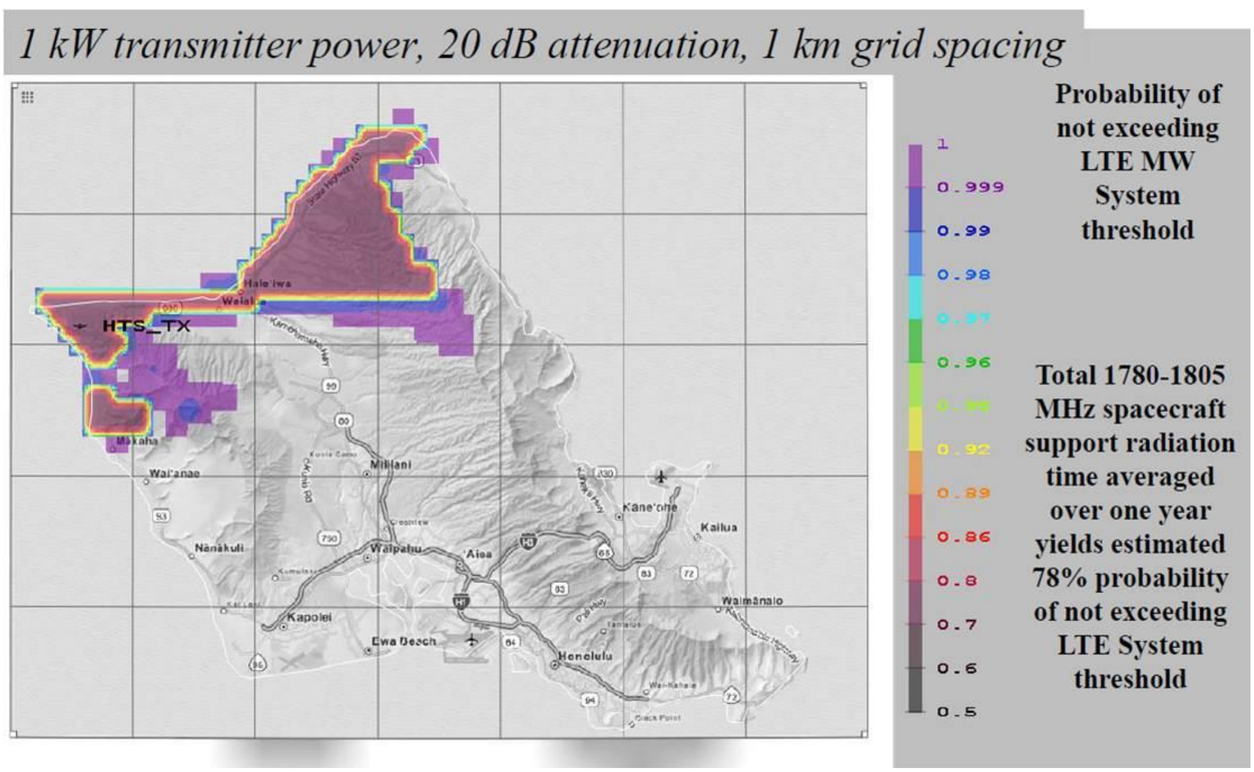


Figure 4.2.4-39 HTS LTE System Threshold Exceedance, 1780-1805 MHz

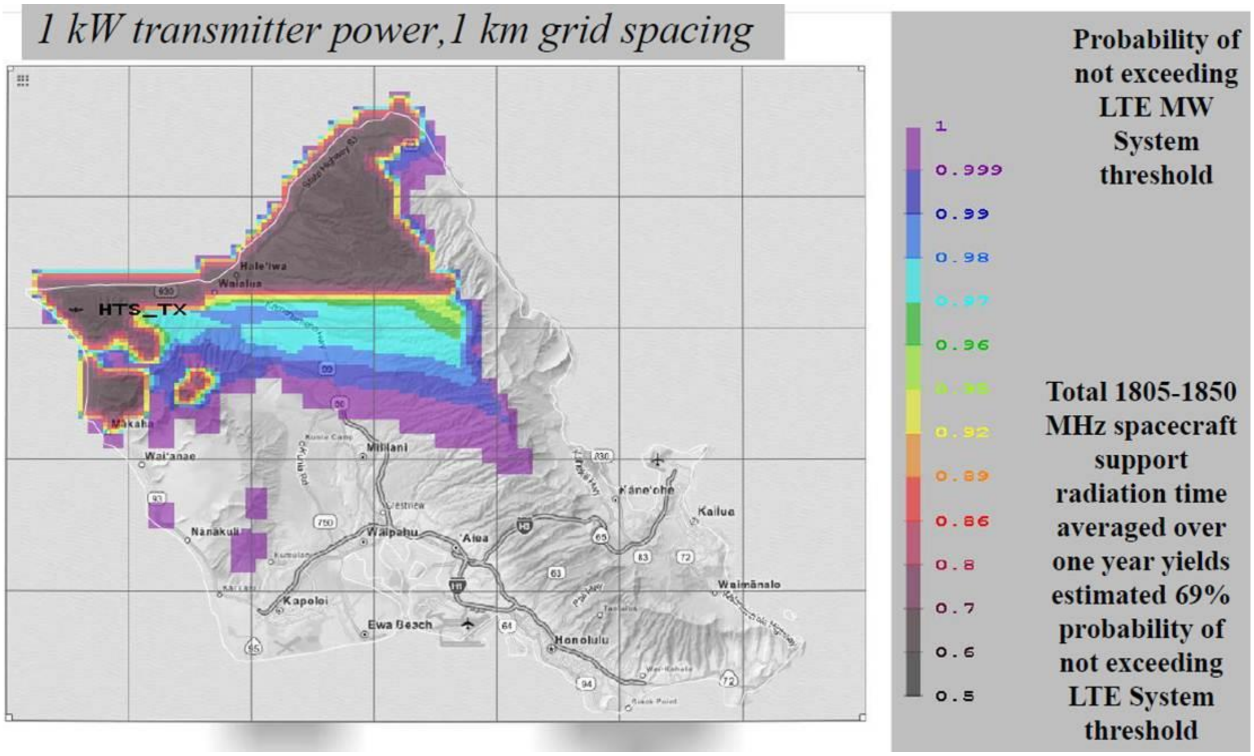


Figure 4.2.4-40 HTS LTE System Threshold Exceedance, 1805-1850 MHz

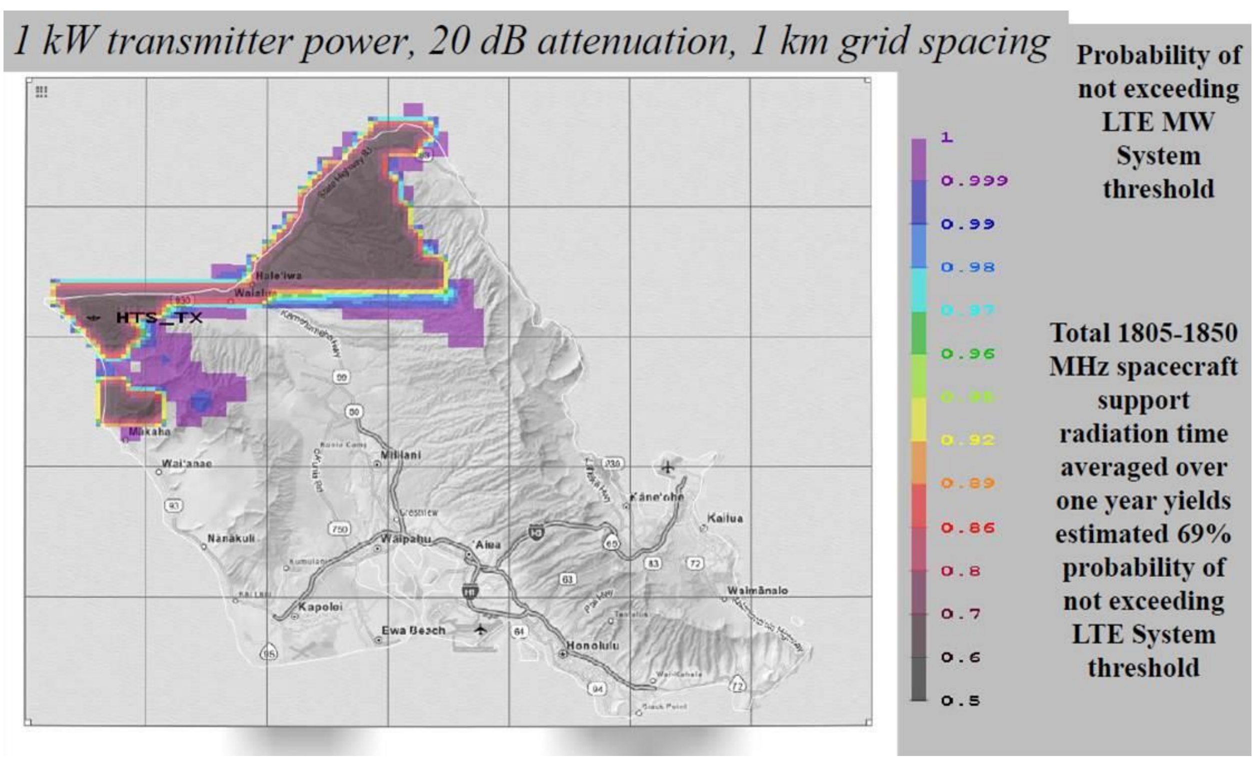


Figure 4.2.4-41 HTS LTE System Threshold Exceedance, 1805-1850 MHz

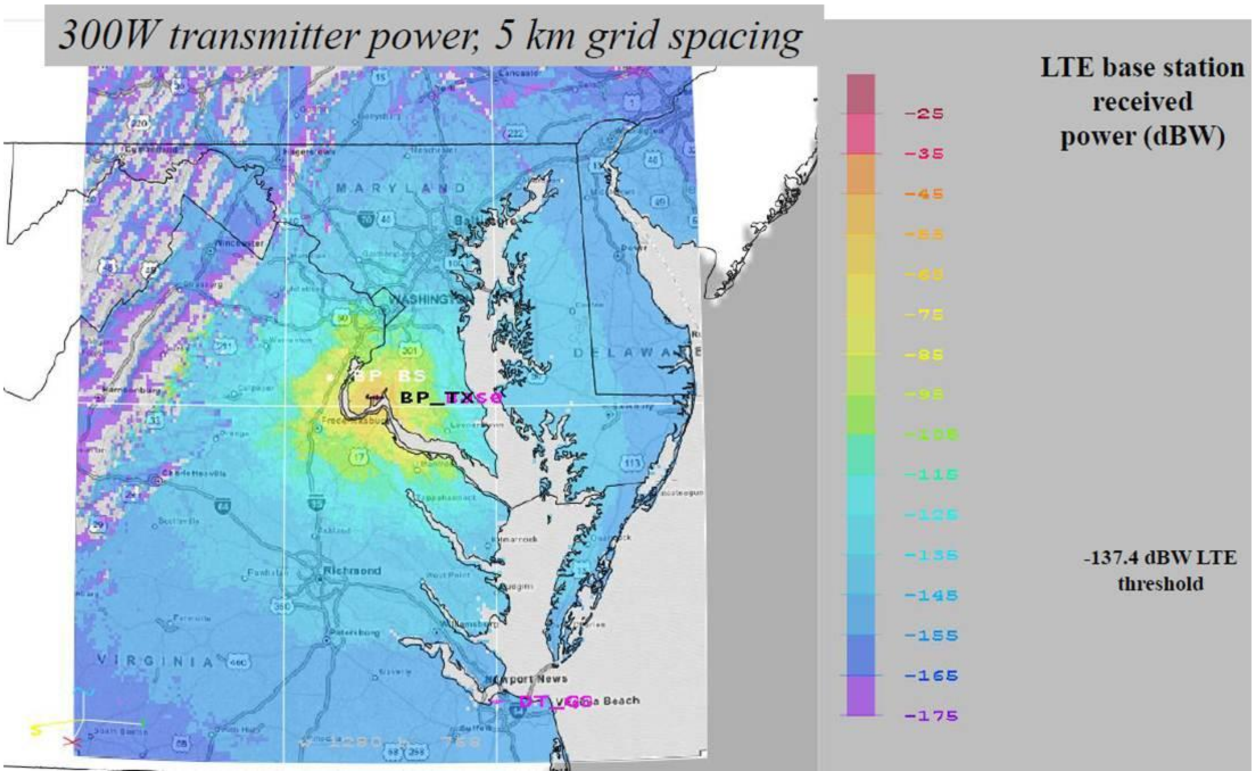


Figure 4.2.4-42 BP, MD Power Contours

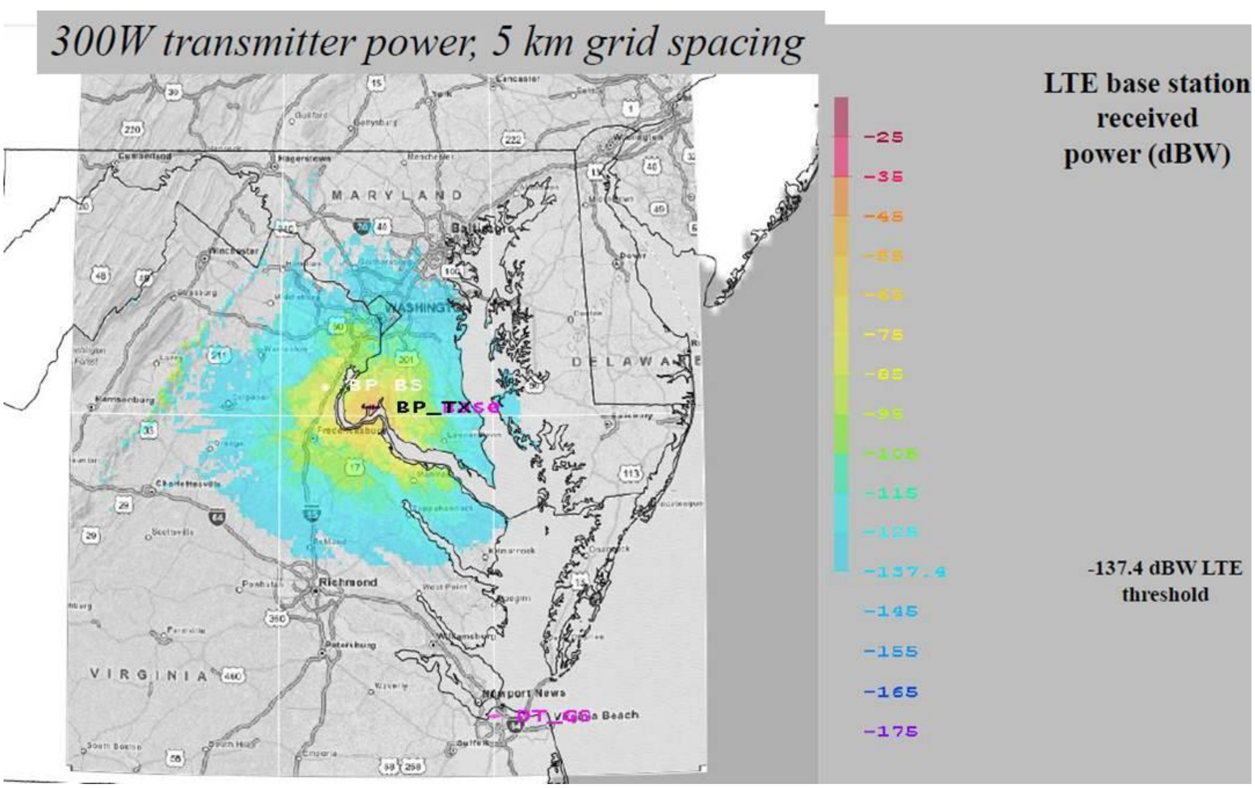


Figure 4.2.4-43 BP, MD Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

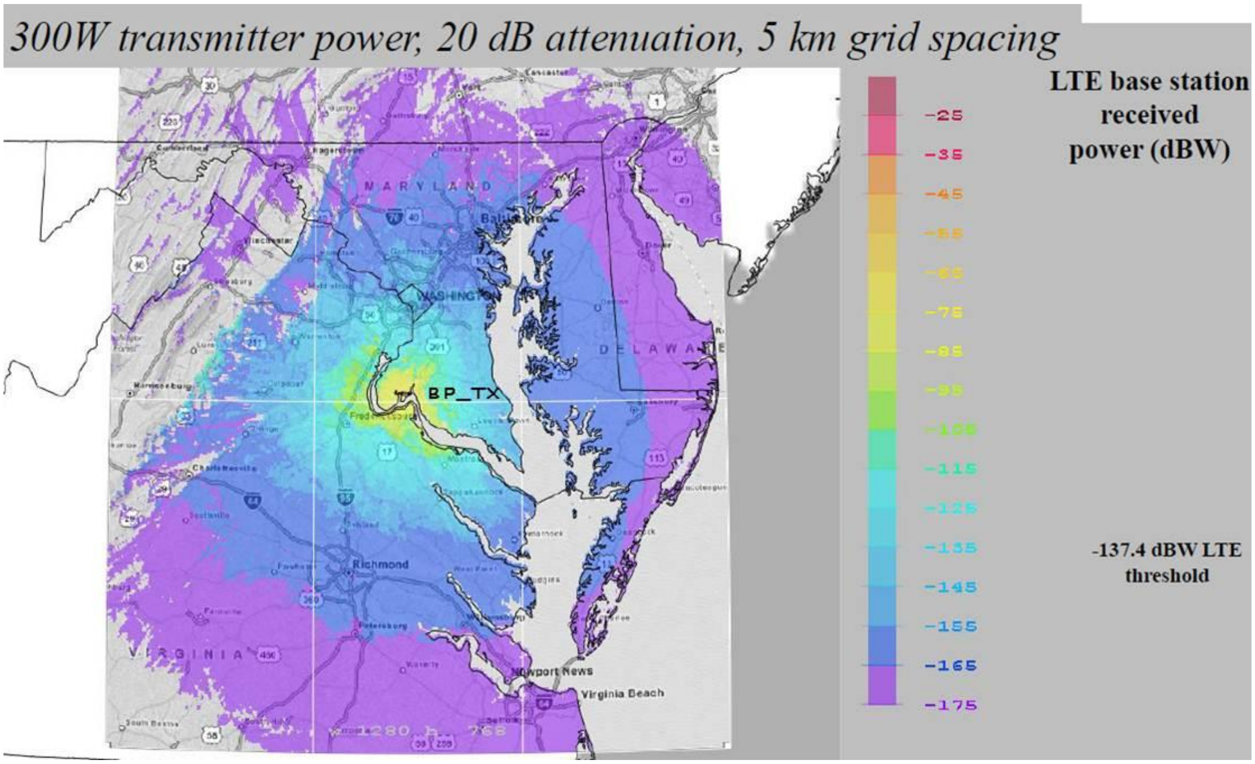


Figure 4.2.4-44 BP, MD Power Contours

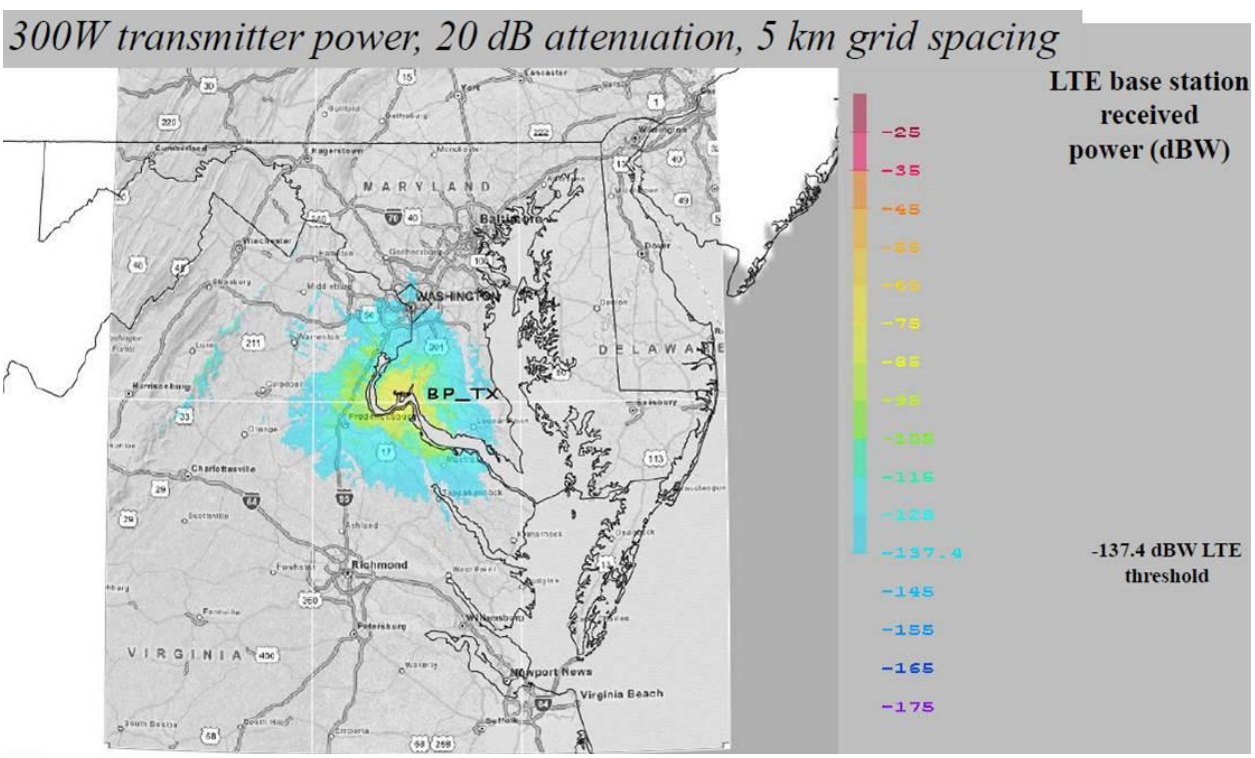


Figure 4.2.4-45 BP, MD Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

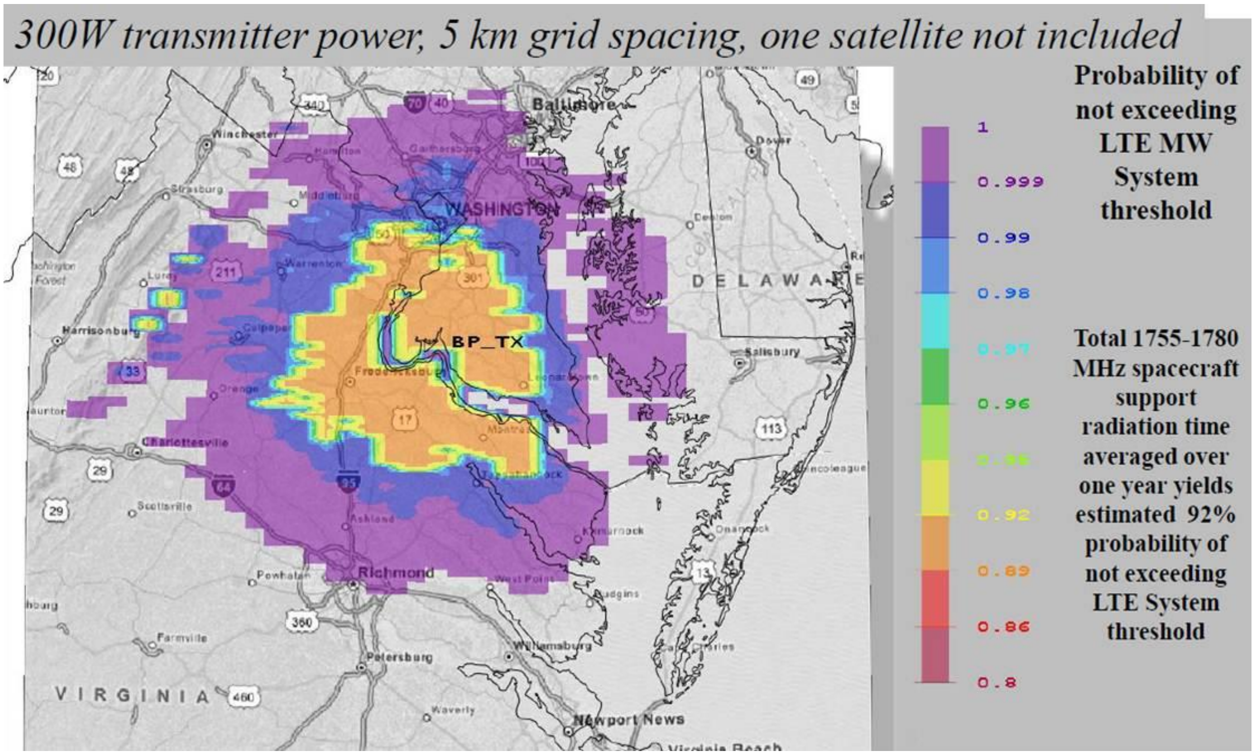


Figure 4.2.4-46 BP, MD LTE System Threshold Exceedance, 1755-1780 MHz

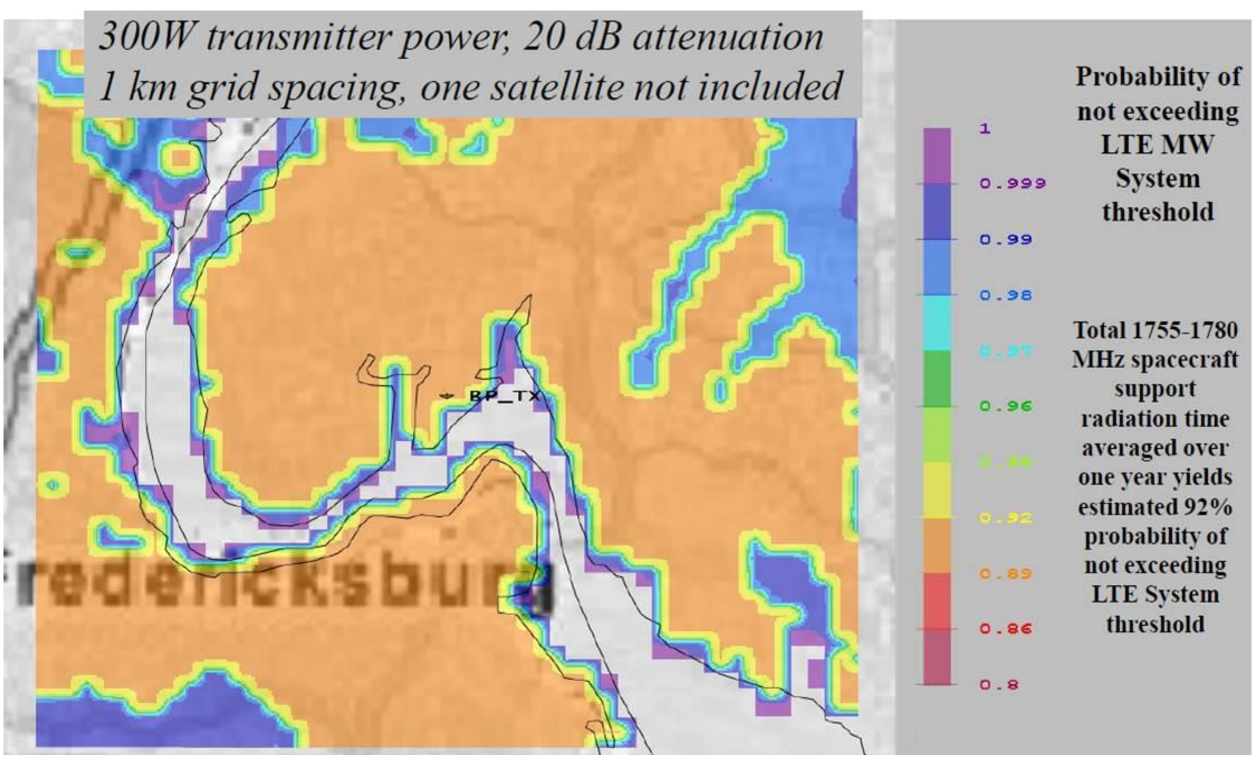


Figure 4.2.4-47 BP, MD LTE System Threshold Exceedance, 1755-1780 MHz

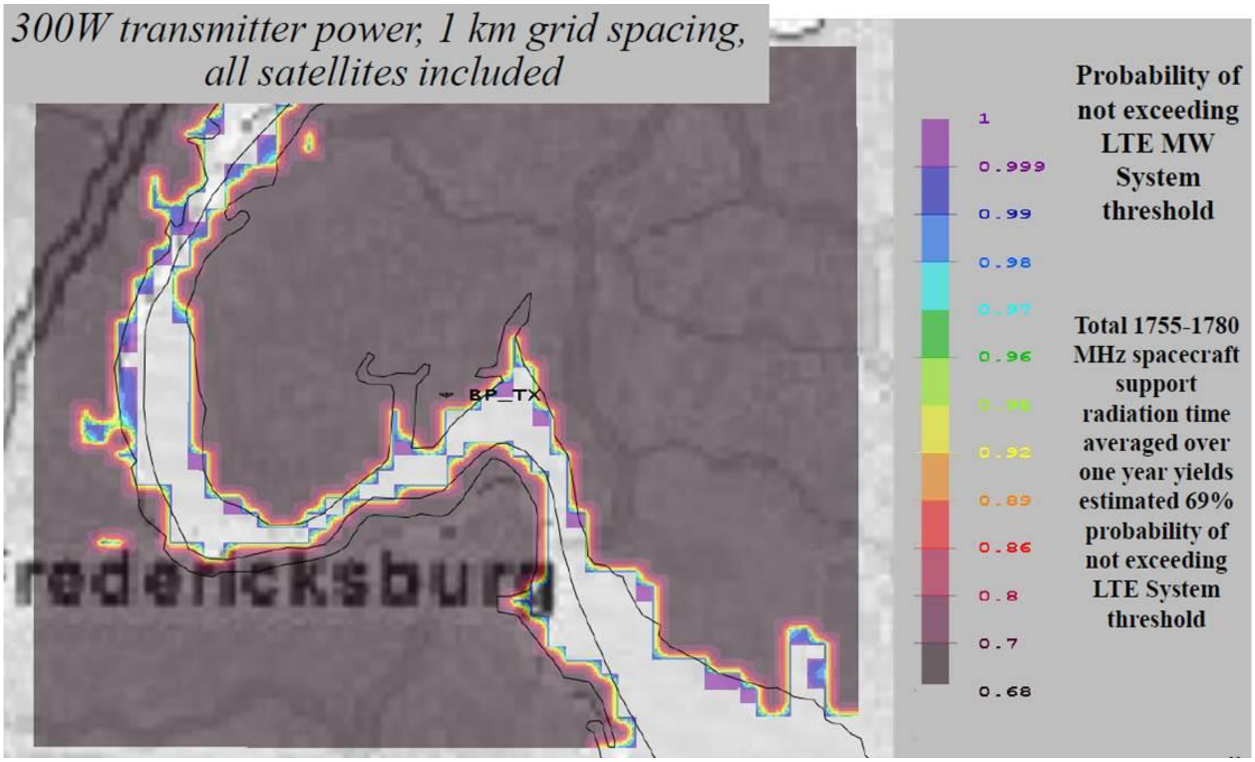


Figure 4.2.4-48 BP, MD LTE System Threshold Exceedance, 1755-1780 MHz

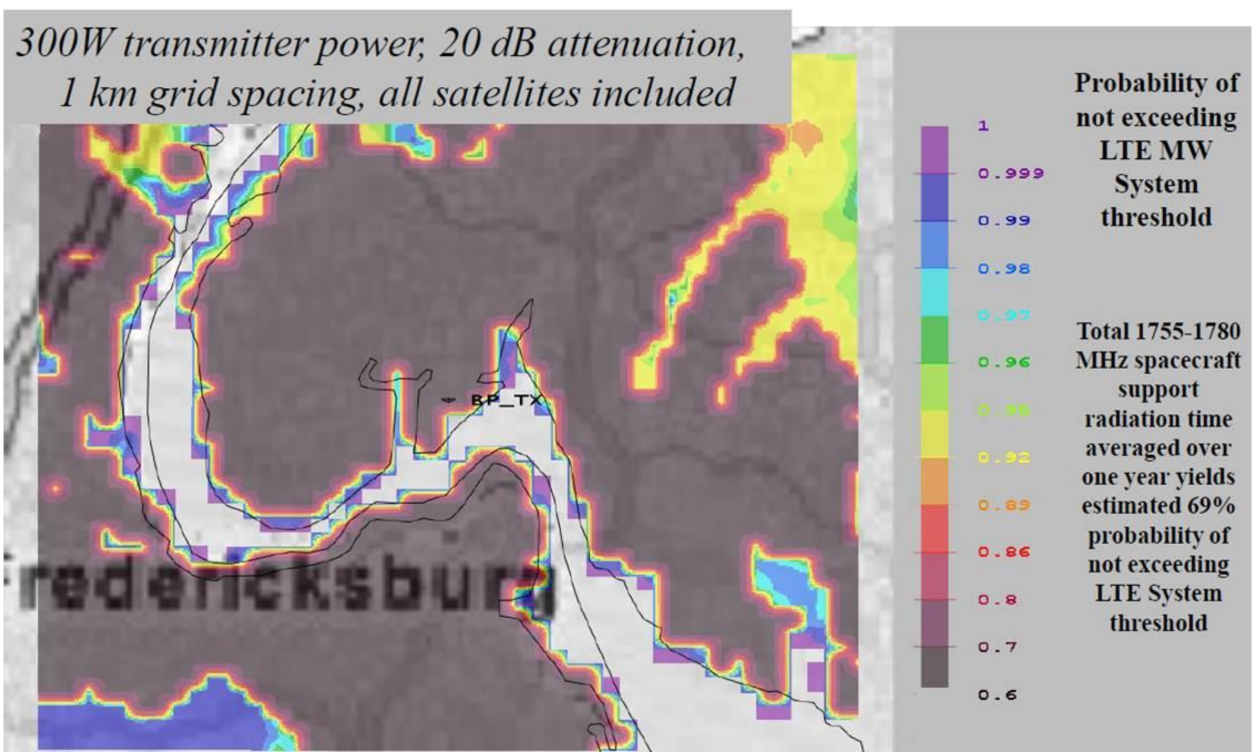


Figure 4.2.4-49 BP, MD LTE System Threshold Exceedance, 1755-1780 MHz

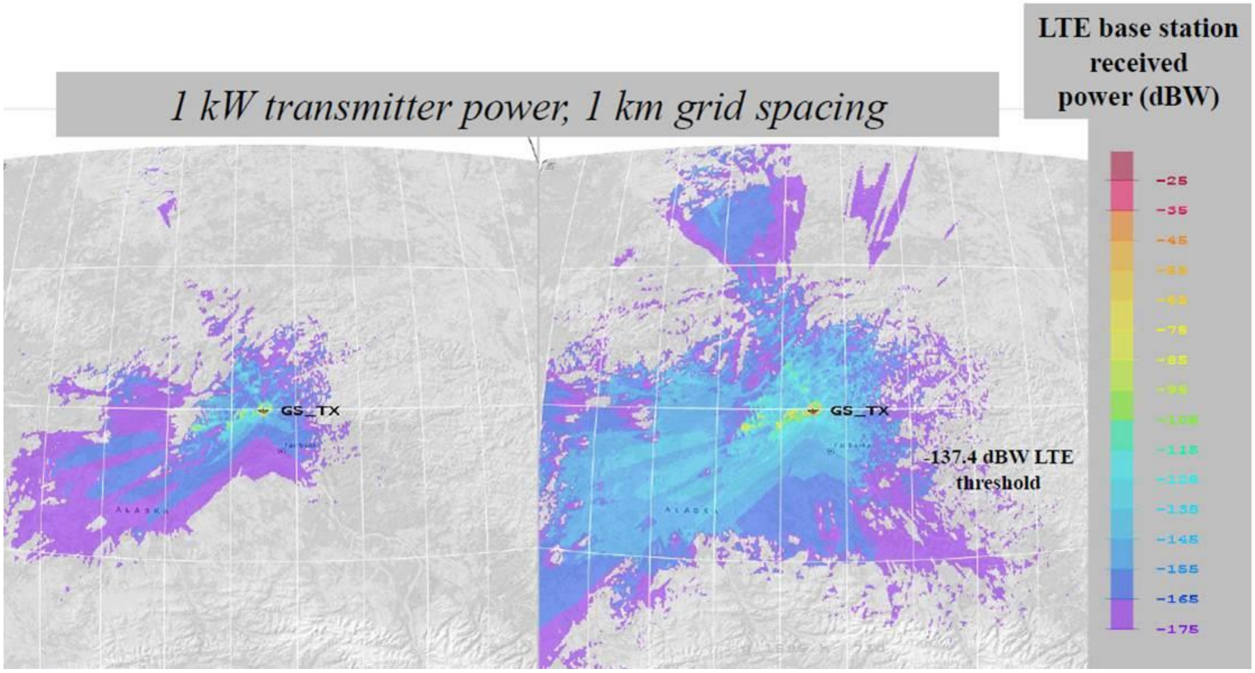


Figure 4.2.4-50 FB, AK Power Contours

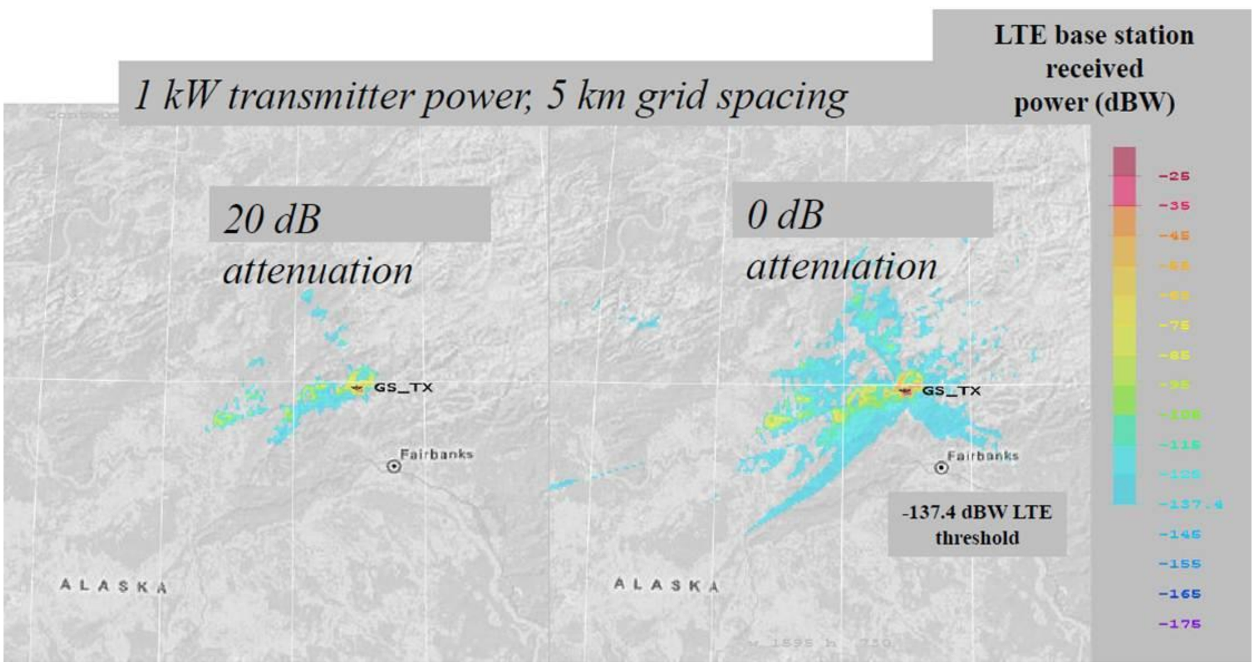


Figure 4.2.4-51 FB, AK Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

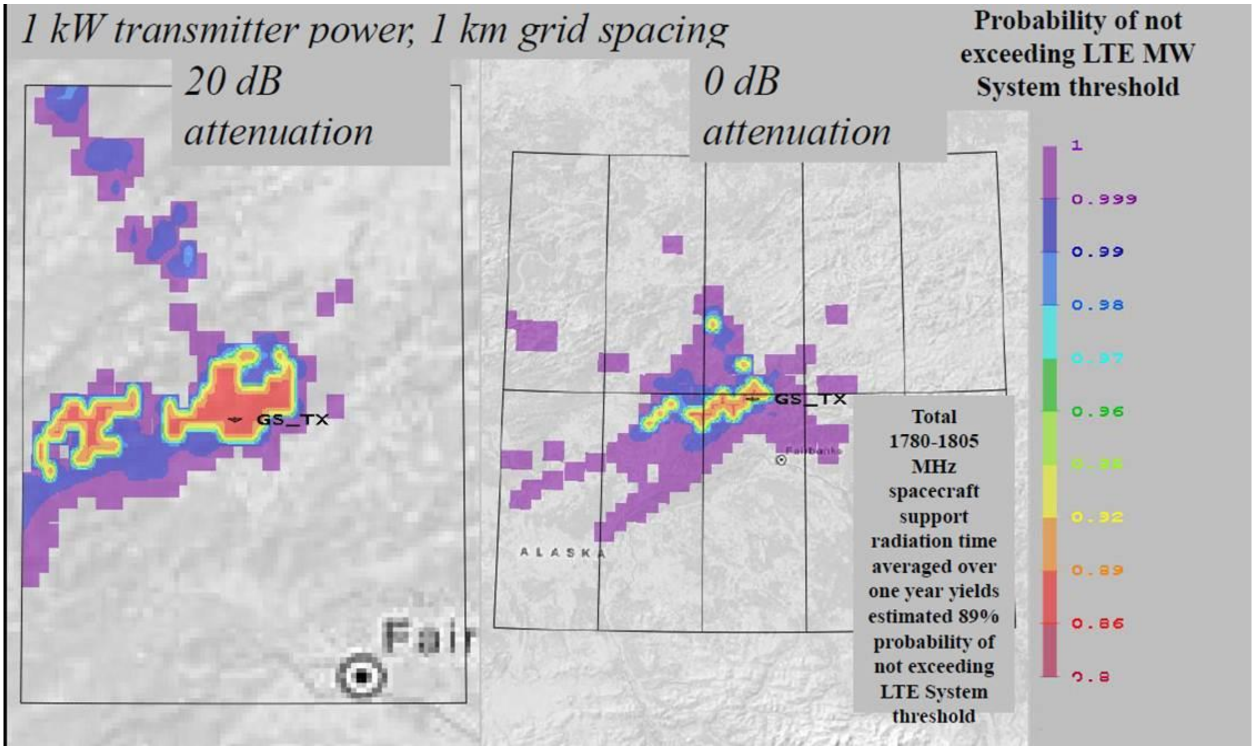


Figure 4.2.4-52 FB, AK LTE System Threshold Exceedance, 1780-1805 MHz

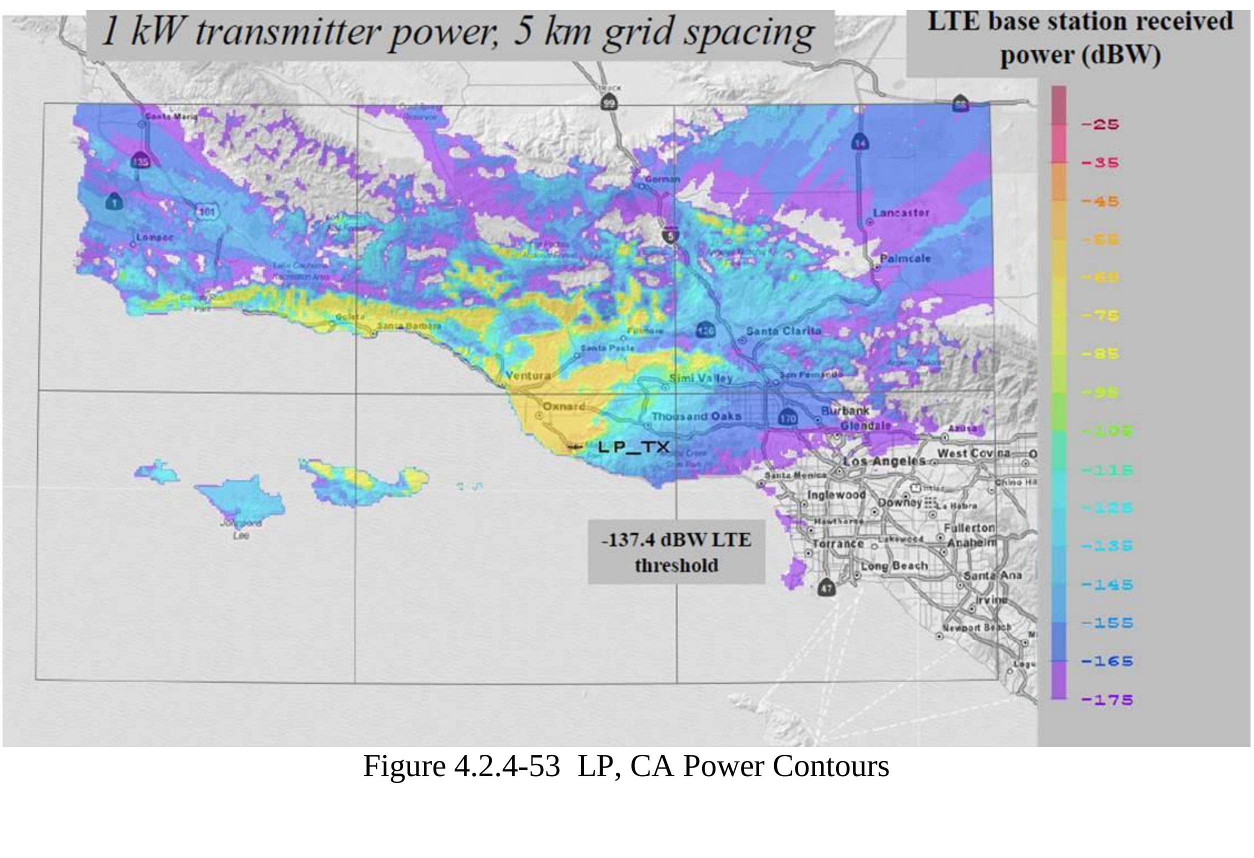


Figure 4.2.4-53 LP, CA Power Contours

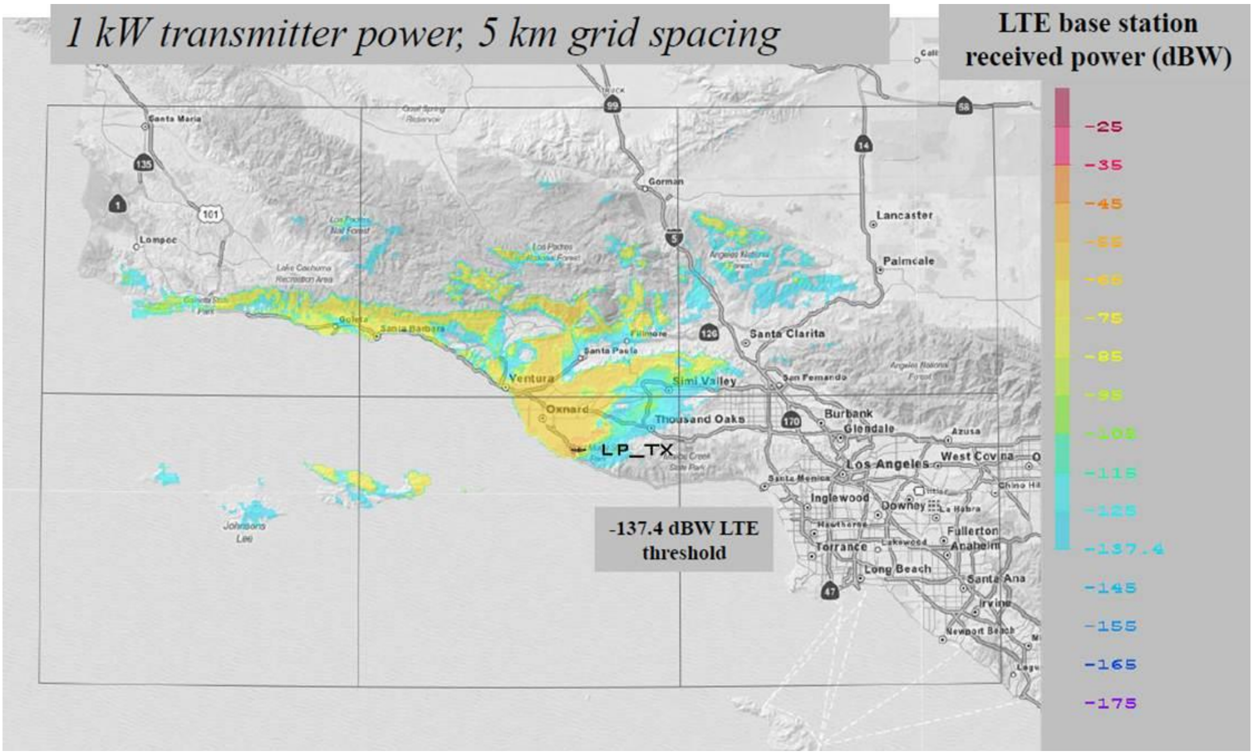


Figure 4.2.4-54 LP, CA Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

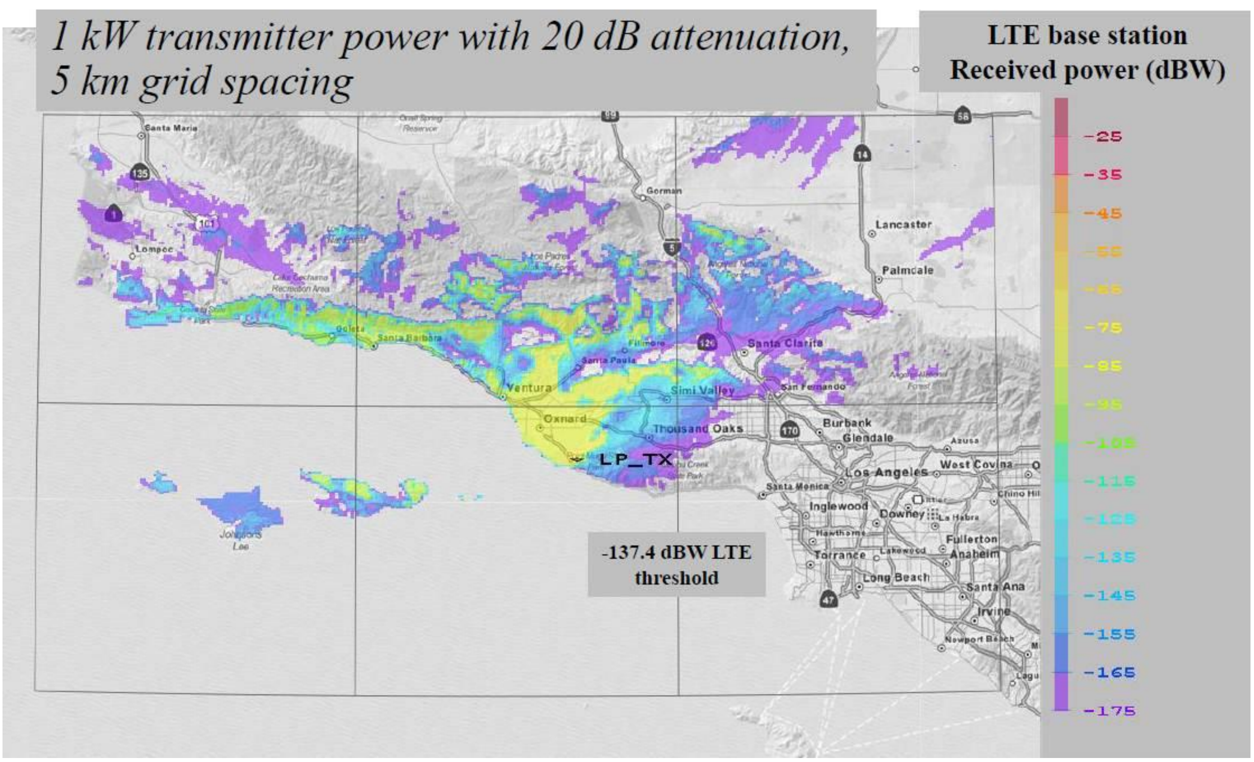


Figure 4.2.4-55 LP, CA Power Contours

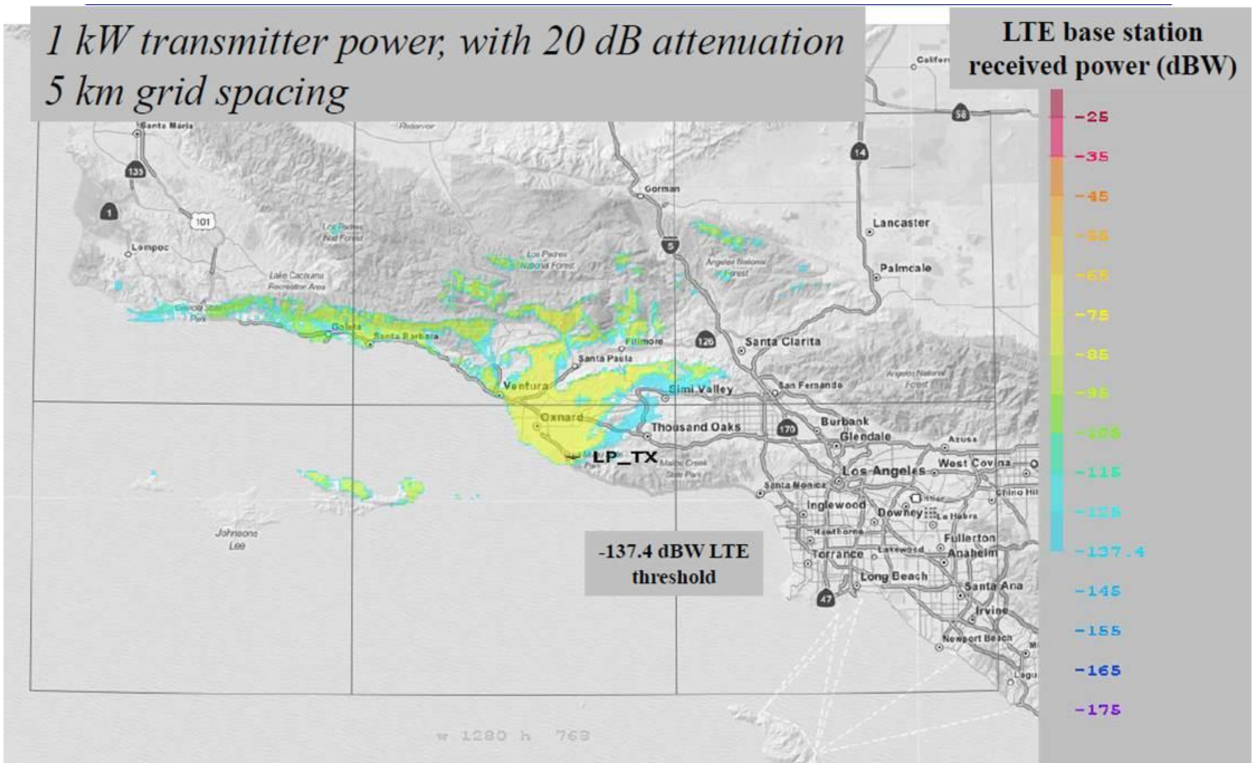


Figure 4.2.4-56 LP, CA Radiated Power With Natural Terrain in Grey Indicating Power Below Threshold

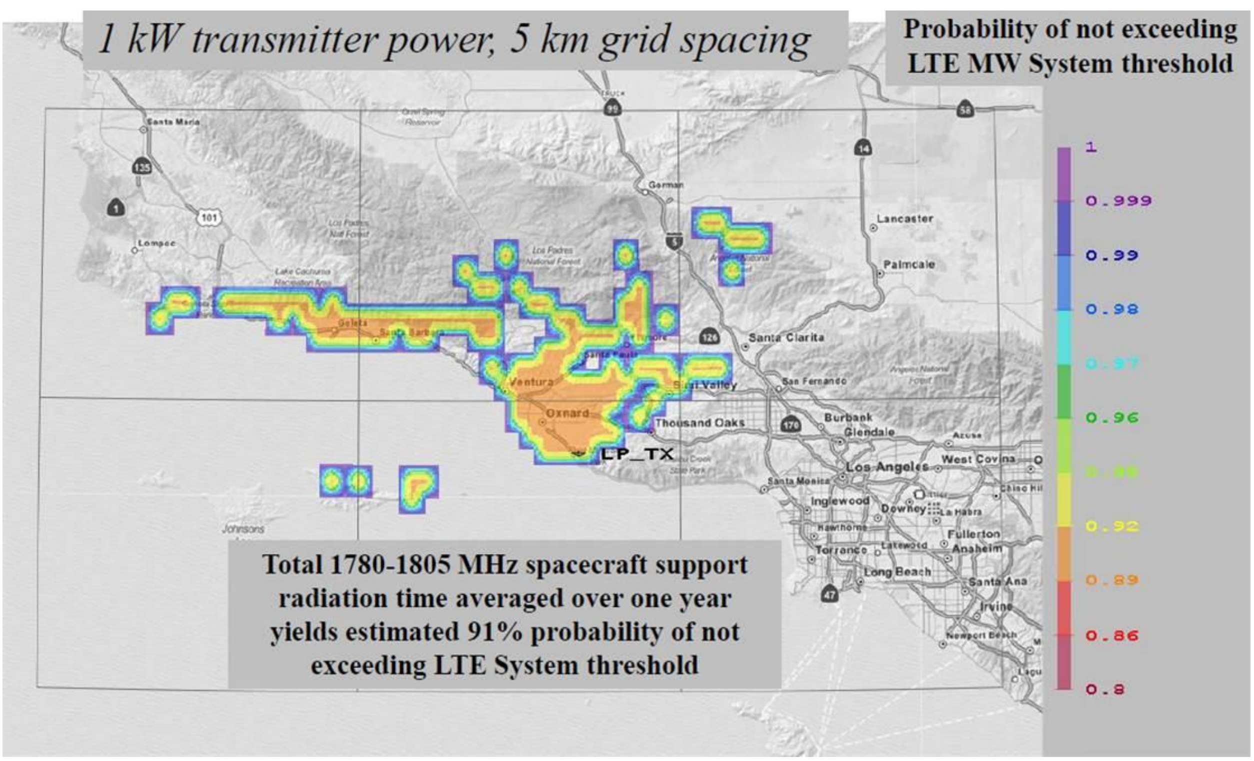


Figure 4.2.4-57 LP, CA LTE System Threshold Exceedance, 1780-1805 MHz

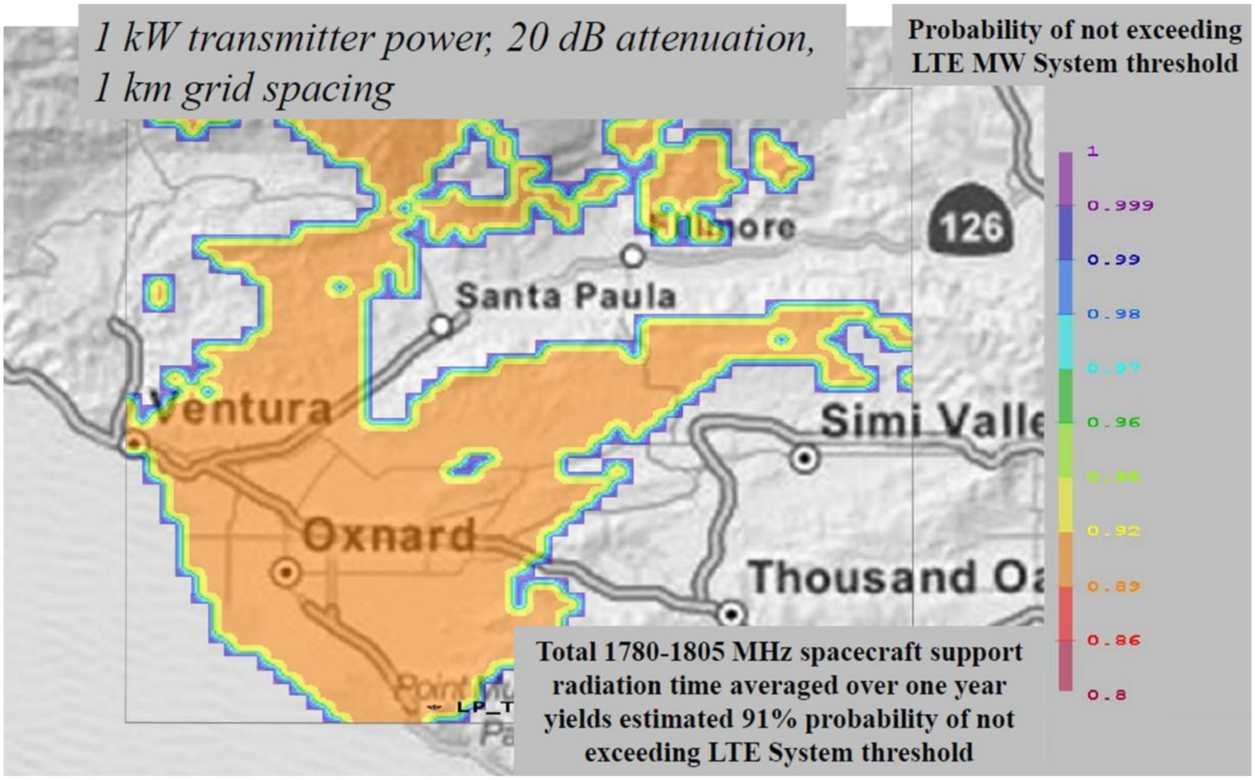


Figure 4.2.4-58 LP, CA LTE System Threshold Exceedance, 1780-1805 MHz

4.2.4.4 Technical Rationale

The following topics are elaborated in this Appendix to Section 4.2.4.2:

- ITM Parameters
- Transmitter and Receiver Parameter Choices
- RFI Overlap for Two Antennas Operating at a Site
- Mathematical definition of Threshold Non-Exceedance Calculation

4.2.4.4.1 Irregular Terrain Model (ITM) - Input Parameter Value Choices

Table 4.2.4-1: ITM Parameters.

Parameter	Selected	Options
Polarization	Vertical	Vertical Horizontal
Radio climate	Contental subtropical	Equatorial Contental subtropical Maritime tropical Desert Contental Temperate Maritime temperate, over land Maritime temperate, over sea
Dielectric constant of ground	15 – Average Ground	4- Poor ground 15 - Average ground 25 - Good ground 81 - Fresh/sea water
Conductivity of ground	0.005 - Average ground	0.001 - Poor ground 0.005 - Average ground 0.02 - Good ground 0.01 - Fresh water 5.00 - Sea water
Reliability statistic values	50%	Greater than zero, less than 100%
Confidence statistic values	50%	Greater than zero, less than 100%
Surface Refractivity	301 - Contental Temperate (Use for Avg. Atmospheric Conditions)	280 - Desert (Sahara) 301 - Contental Temperate (Use for Avg. Atmospheric Conditions) 320 - Continental Subtropical (Sudan) / Maritime Temperate, Over Land (UK and Contenital West Coast) 350 - Maritime Temperate, Over Sea 360 - Equatorial (Congo) 370 - Maritime Subtropical (West Coast of Africa)

4.2.4.4.2 Transmitter and Receiver Parameter Choices

Table 4.2.4-2: Transmitter and Receiver Parameter Choices.

Parameter	Selected
Transmitter Frequency (MHz)	1762
Transmitter Power (dBm)	60
Peak Antenna Gain (dBi)	Site Dependent
Antenna Gain at Horizon[32] (dBi)	16
EIRP @ Horizon	Site Dependent
Transmitter Antenna Height (m)	30
Receiver Antenna Height (m)	30
Receiver Antenna Down tilt (deg)	3
Receiver 3dB Beamwidth (el) (deg)	10
Receiver 3dB Beamwidth (az) (deg)	70
Receiver Antenna Gain at Horizon (dBi)	18
Receiver Ref Sensitivity (dBm)	-101.5
Receiver Interference @ 1 dB desense (dBm)	-107.37
Receiver Interference @ 3 dB desense (dBm)	-101.5
Receiver Sensitivity (1 dB desense, dBW)	-207.94
Receiver Sensitivity (3 dB desense, dBW)	-202.07

Note that the analysis assumes the LTE antenna is pointing at the SATOPS antenna, in azimuth.

4.2.4.4.3 Modeling of RFI Overlap for 2 Antennas

Radiation time for each antenna pointing angle was delivered as a sum of the time radiated in that direction by antenna A and the time radiated in that direction by antenna B. This causes some radiation time and thus some threshold exceedance time to be double-counted.

The overlapping threshold exceedance time can be described as:

$$PRFI\ Overlap=Pant\ A\ onANDant\ A\ exceeding\ thresholdANDant\ B\ onANDant\ B\ exceeding\ threshold$$

This double-counted time was calculated and removed from the threshold exceedance times.

4.2.4.4.4 RFI Overlap for 2 Antennas Calculation

Assuming independence between antenna A and antenna B,

$$P(RFI\ Overlap) = P(ant\ A\ on) * P(ant\ A\ exceeds\ threshold \mid ant\ A\ on) * P(ant\ B\ on) * P(ant\ B\ exceeds\ threshold \mid ant\ B\ on)$$

[32] "Antenna Models for Electromagnetic Compatibility Analyses," NTIATM-13-489, National Telecommunication and Information Administration Technical Memorandum, October 2012.

Assuming the same radiation time for and received power distribution from the 2 antennas,

$$P(ant\ A\ on) = P(ant\ B\ on)$$

$$P(ant\ A\ exceeds\ threshold \mid ant\ A\ on) = P(ant\ B\ exceeds\ threshold \mid ant\ B\ on)$$

then

$$\begin{aligned} P(RFI\ Overlap) &= 2 * P(ant\ A\ on) * 2 * P(ant\ A\ exceeds\ threshold \mid ant\ A\ on) \\ &= 2 * [(Radiate\ \%/2) * P(ant\ A\ exceeds\ threshold \mid ant\ A\ on)] \\ &= 2 * (Threshold\ Exceedance\ \%/2) \end{aligned}$$

$2 * (Threshold\ Exceedance\ \%/2)$ is the correction factor that was used to remove double-counted threshold exceedance times from our calculations

Non-Exceedance Calculation:

- Non-Exceedance Calculation is

$$P(NE) = \sum_{i=1}^{n}\sum_{j=1}^{m} P\left(NE \left| \left[Az_i \bigcap El_j\right]\right.\right) P\left(Az_i \bigcap El_j\right) + \left[1 - \sum_{i=1}^{n}\sum_{j=1}^{m} P\left(Az_i \bigcap El_j\right)\right]$$

where $P(NE)$= Probability of Non-Exceedance

(Equation excludes correction factor discussed earlier)

- Without Variance:

$P\left(NE \left| \left[Az_i \cap El_j\right]\right.\right)$ is strictly 1 or 0 based on the following condition

$$P\left(NE \left| \left[Az_i \bigcap El_j\right]\right.\right) = \begin{cases} 1\ if\ MeanRxPwr < Threshold \\ 0\ if\ MeanRxPwr\ \geq Threshold \end{cases}$$

- With Variance:

$P\left(NE \left| \left[Az_i \cap El_j\right]\right.\right)$ is based on the Q-function because received power for a given Az/El pointing direction is log normal and follows the condition

$$P\left(NE \left| \left[Az_i \bigcap El_j\right]\right.\right) = 1 - Q\left(\frac{Threshold - MeanRxPwr}{\sigma}\right)$$

4.2.5 Mitigation Concepts into LTE Base Station Receivers

Mitigation techniques are very important to facilitate the operation of mobile broadband systems close to SATOPS ground stations. The following illustrative example shows the possible benefit of mitigation in general.

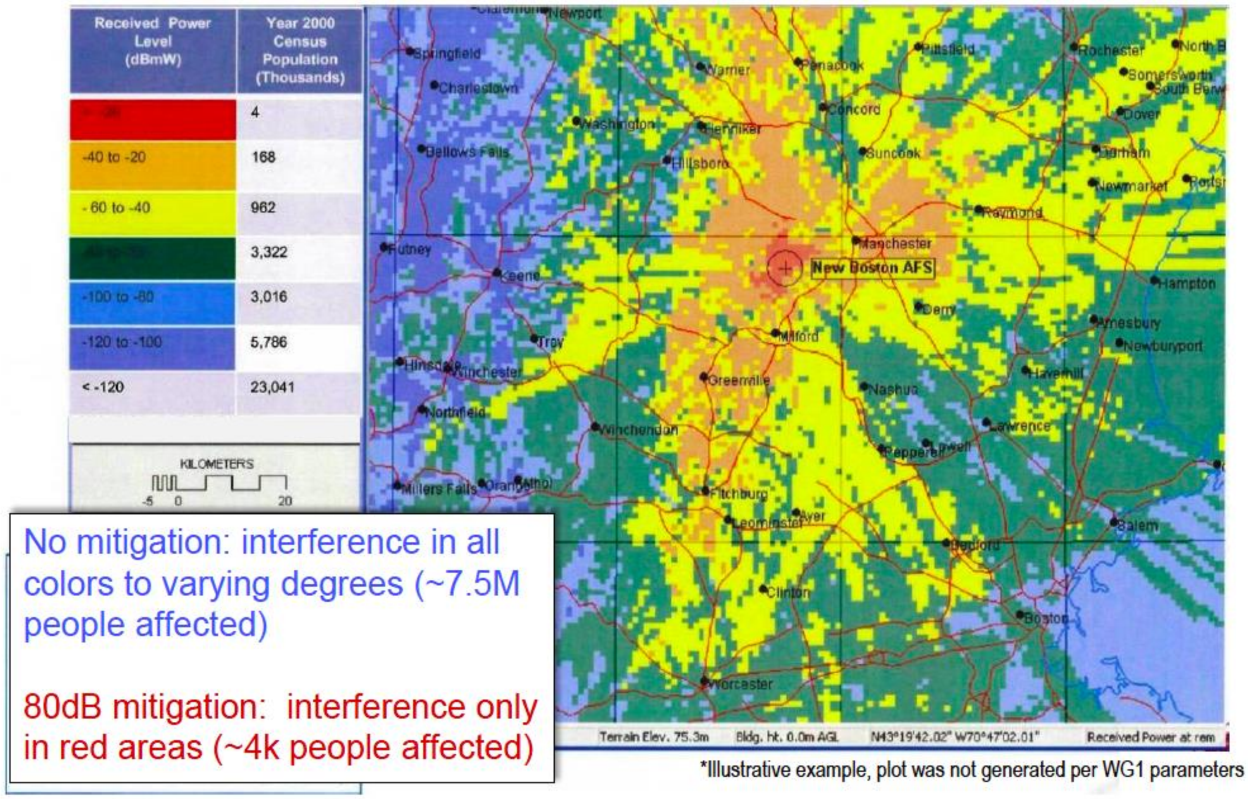


Figure 4.2.5-1. Possible Benefit of Mitigation.

There are numerous mitigation techniques that appear to offer the opportunity for SATOPS ground stations to coexist with LTE systems under certain conditions. These include options listed in Table 4.2.5-1. The mitigation techniques are listed in alphabetical order. Effectiveness and feasibility may vary case-by-case. Each mitigation technique is discussed in detail in the remainder of this section.

While all the mitigation schemes offered in Table 4.2.5-1 under the heading “Concept” are theoretically plausible, it should be noted that the cost of technical research, prototyping, proof of concept testing, standardization, and development of the commercial products for implementing any of these techniques may not be trivial, even if such techniques prove to be practical and applicable to the case of LTE operation near the SATOPS ground stations.

The RF shielding around the SATOPS ground station seems to offer a very good solution and possibly the most attractive in terms of its cost-effectiveness, applicability and practicality of the technique that is involved, however the construction lag could limit the use of the shared spectrum for a considerable period of time.

Since the implementation of time sharing, which is the exchange of operational schedules between the commercial operator and the SATOPS operator, greatly depend on the predictability of the SATOPS ground station transmission times. This information is classified and for security concerns cannot be made available to the LTE operators, the time sharing technique cannot be considered as a practical mitigation scheme at the present time.

It is also technically possible for the LTE base stations to avoid using the shared spectrum in the “interference zones” and thereby mitigate the interference from the SATOPS ground stations. However, this method (i.e. the Frequency Selective Scheduling (FSS) that detects and avoids the interference after channel sounding) is not part of the standards and its realization depends on the vendor-specific product. As FSS is not generally available to LTE operators at this time, its implementation again would impose the above-mentioned cost and time constraints.

When FSS is not available, the entire shared spectrum must then be avoided so as not to compromise the offered mobile data rates during the SATOPS transmission times. Since the mobile data traffic demand in the “interference zones” around the existing SATOPS ground stations is not expected to be as high as the demand in the more densely populated urban areas, relying on the other bands available to an operator and not using the shared spectrum would certainly be a viable alternative, but this would be tantamount to the mobile operator forfeiting one-sidedly its right to use of the shared spectrum.

It would be therefore appropriate to consider these factors, as well as the cost of research, development, realization, and implementation of any these methods, including the required time intervals, in the valuation of the shared spectrum in the forthcoming auctions. These mitigation options will change with time and may be possible in the future.

Table 4.2.5-1: Discussed mitigation concepts to enhance co-existence between SATOPS uplink transmit operations and LTE base station receivers

Concept	Implementation
AFSCN digital waveform upgrade	SATOPS
Base station accepts more interference	BS
Cell Tower Antenna Configuration	BS
Digital Ranging Cancellation	BS
Dual Band	SATOPS
Front End Signal Cancellation	BS
Limit use of SATOPS	SATOPS
Multiple In/Multiple Out (MIMO)	BS
Offloading/ Scheduling	SATOPS
Operational Pointing Restrictions	SATOPS
Reduce Antenna Sidelobes	SATOPS
SATOPS site relocation	SATOPS
Selection of SATOPS channels	SATOPS
Selective Receiver RF Filtering	BS
Self Optimizing networks (SON)	BS
Spectrum Efficient Waveform	SATOPS
Spectrum Landscaping/ Shielding	BS or SATOPS
Time / Frequency Sharing[33]	BS
Uplink Power Control	SATOPS

4.2.5.1 AFSCN Digital Waveforms

The AFSCN upgrade to digital equipment is currently underway but may take substantial number of years. This upgrade will reduce emission bandwidths for SATOPS uplinks from AFSCN sites. For example, a commonly used uplink emission will be reduced from 900 kHz to a 225 kHz bandwidth within -20 dB from peak power. The upgraded signal structure for this example is shown in Figure 4.2.1-3. Such an upgrade could be applied to additional AF, Navy and other sites as well if funds are allocated to the Government for complete system wide implementation. The equipment needed for this smaller bandwidth, when implemented, will reduce out-of-band energy and the amount of bandwidth impacted at the cellular base station. Implementation at sites other than the AFSCN would take at least 5 years from start of implementation, given appropriate funding.

4.2.5.2 Cell Tower Antenna Configurations

By planning the deployment of cell towers surrounding a SATOPS site, Government/industry co-existence can be enhanced by orienting the sectors so that the main beam of the cellular antenna is never pointed in the direction of a SATOPS terminal. Another method is the use of antenna down tilt on the cellular base stations. These mitigation techniques were evaluated in the analysis of section 4.2.1 and can provide anywhere from 11.4 to 30.4 dB based on the data in

[33] Time/Frequency sharing is also referred to as Dynamic Spectrum Access (DSA)

section 4.2.1.2.3. The concept is shown in the below figures. The application of these techniques will be limited by a tradeoff with reduction in effective base station coverage area.

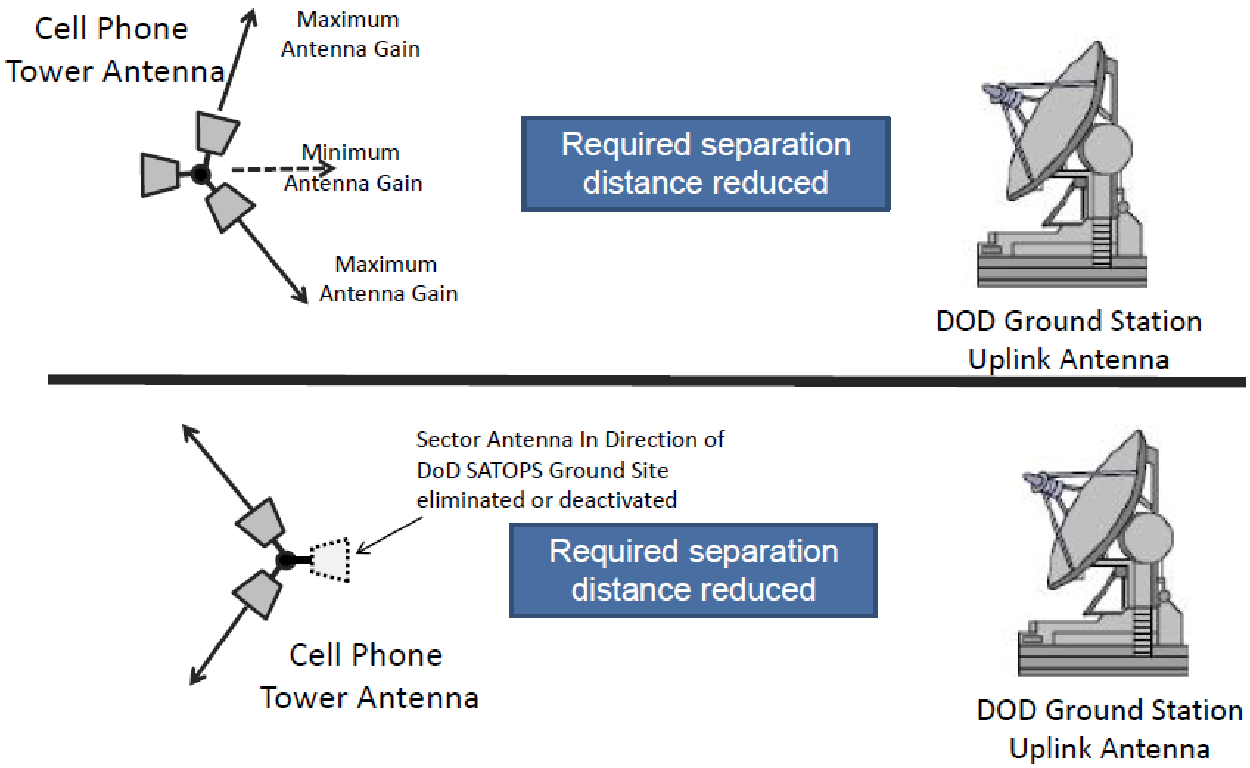


Figure 4.2.5-2.Cell tower antenna sector configuration to enhance co-existence.

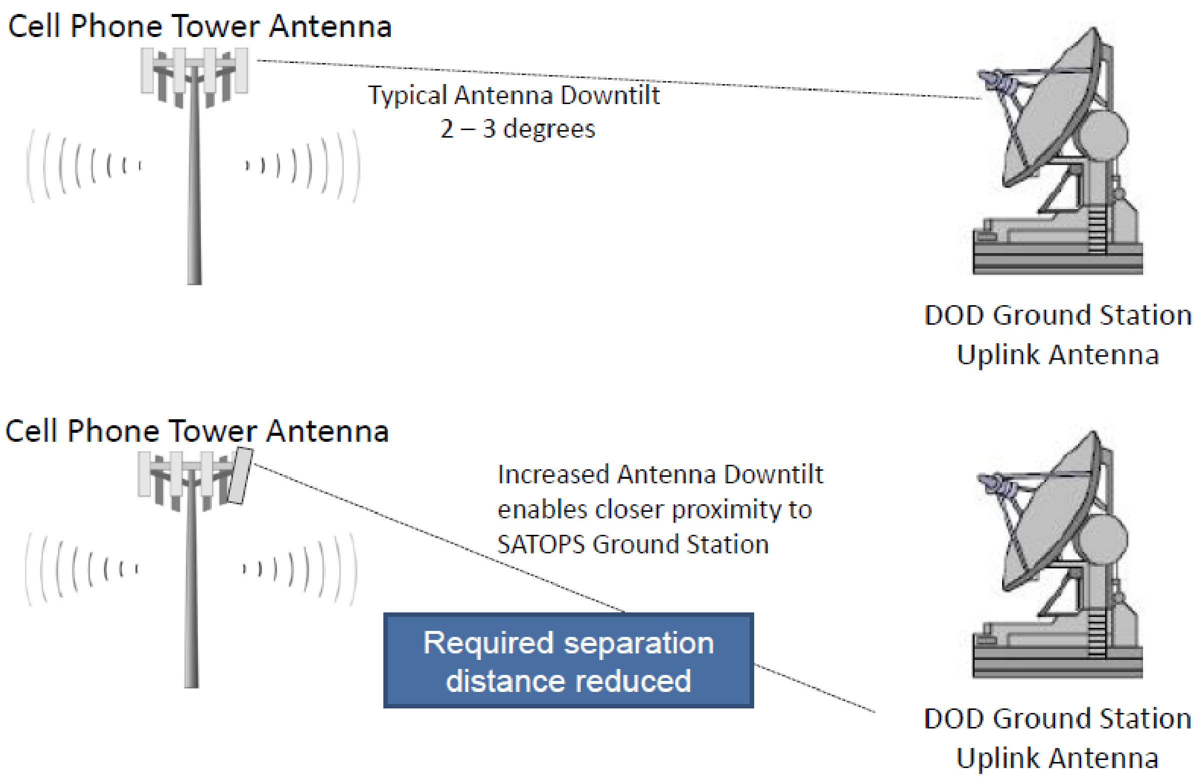


Figure 4.2.5-3.Cell tower antenna down tilt to enhance co-existence.

4.2.5.3 SATOPS Signal Cancellation

Interference cancellation techniques have been studied extensively for their application to mobile wireless system[34], are expected to be included in future releases of LTE, and have been demonstrated to improve the performance of LTE. Application of these and other similar techniques could be effective for mitigating interference from SATOPS signals, especially because such techniques perform best when there is significant difference between the power levels of desired and interfering signals. Although cancellation techniques are anticipated for future releases of LTE, near-term implementations are also possible. A cancellation black box could be designed to operate in between the base station antenna and receiver input that would be capable of detecting the presence of a SATOPS signal and performing the cancellation. While exact performance would be situation dependent and also subject to cost, high performance improvement (approximately up to 30 dB reduction in effective interference power) may be achievable. Cost factors would include the design of the cancellation box and the cost to procure and install it on each base station. This may be cost prohibitive to apply to all base stations in the vicinity of SATOPS sites, but may be effective for specific base stations in particularly desirable market areas. The cancellation box would require its own RF front end, which would add to the cost, but could also allow for additional dynamic range and help to avoid receiver saturation

[34] Andrews, Jeffrey "Interference Cancellation for Cellular Systems; a Contemporary Overview" IEEE Wireless communications, April 2005

caused by the high power SATOPS signal. Figure 4.2.5-4 illustrates the cancellation box approach.

It is also possible that some level of interference cancellation could be implemented through software within the digital signal processors of the base station. This may be achievable with limited processing power given the known structure of the SATOPS signal. The portion of the SATOPS signal used for ranging may be particularly suitable for software cancellation given that it is a pseudorandom high rate signal. Cancellation of the ranging signal would not eliminate interference from the entire SATOPS signal, but could reduce the bandwidth impacted by the interference e.g., from 2 MHz to 200 kHz. This could be effective in combination with other mitigation techniques targeted at mitigating narrow band interference, such as time/frequency sharing (which is discussed in section 4.2.5.15). Given that the commanding portion of the signal has the majority of the signal energy this may be the dominant interfering component which could even cause receiver saturation, thus the effectiveness of cancelling the ranging signal only may be limited. Figure 4.2.5-5 illustrates the software implementation of interference cancellation.

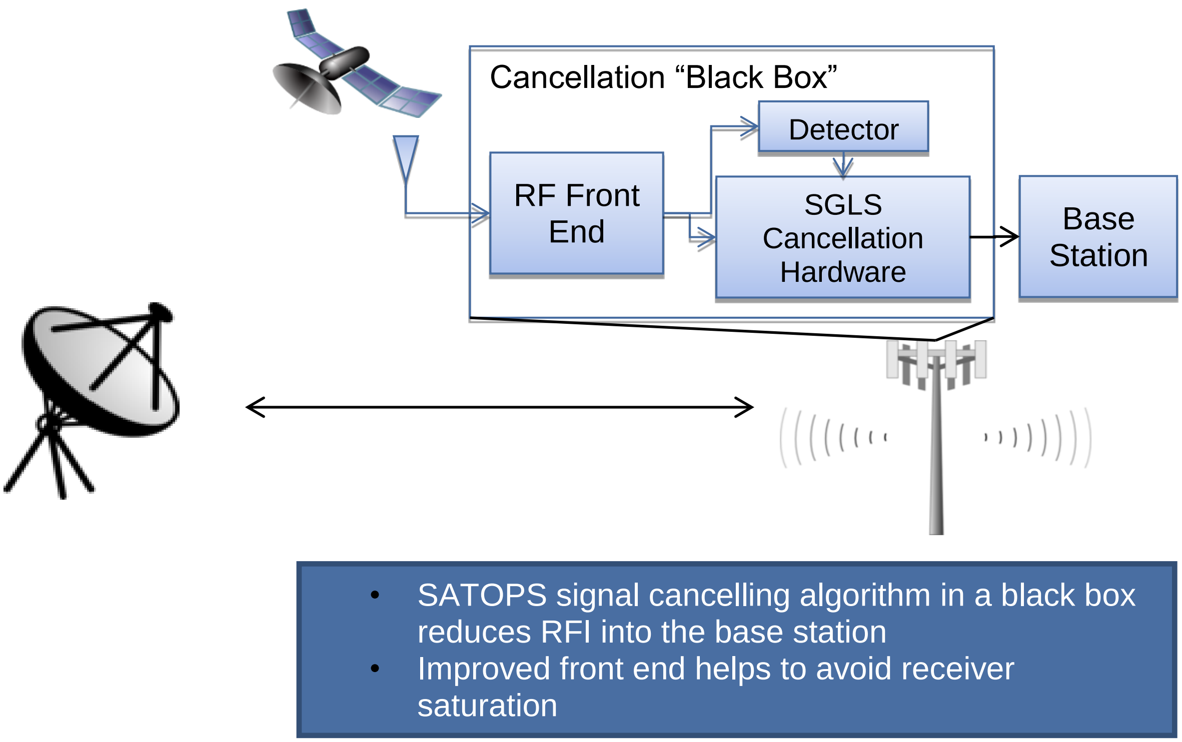


Figure 4.2.5-4. SGLS cancellation hardware to minimize RFI and avoid receiver saturation.

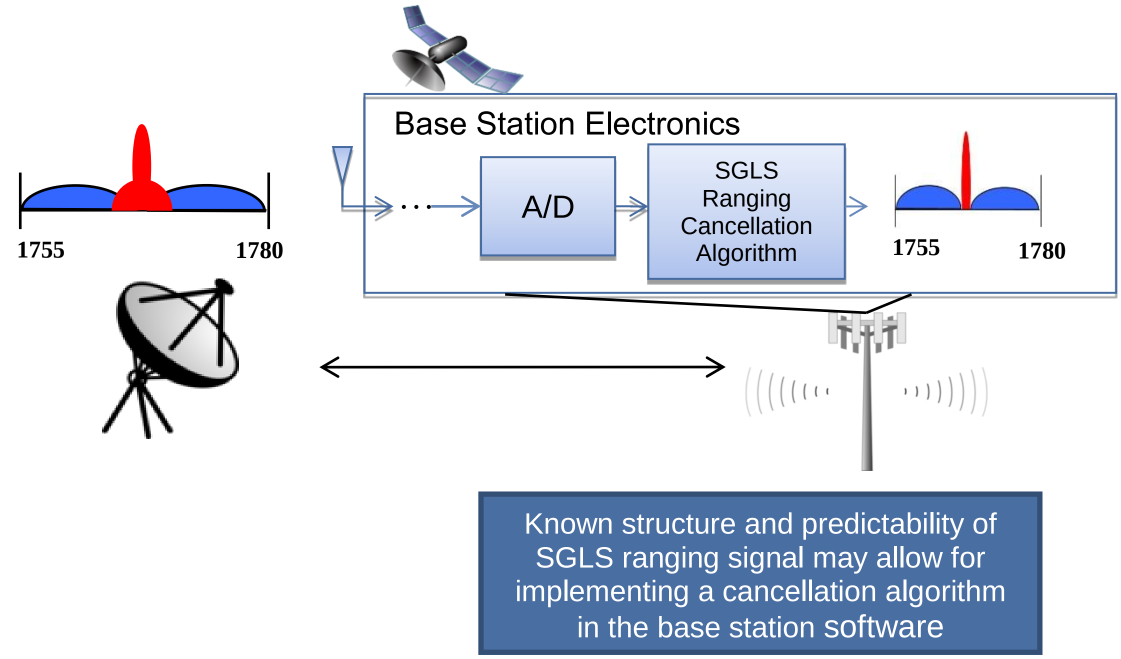


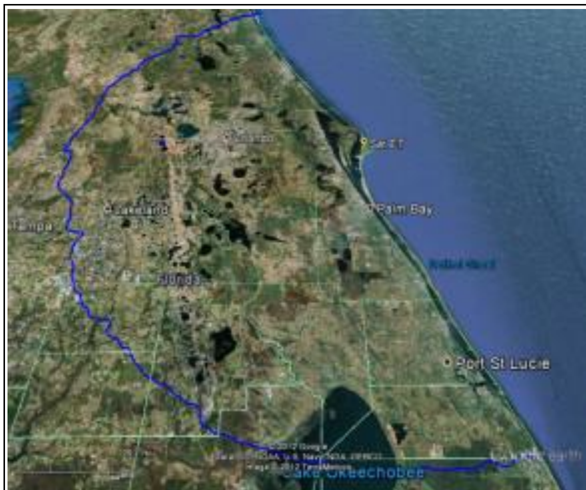
Figure 4.2.5-5. SGLS Ranging cancellation algorithm to reduce the bandwidth of RFI.

4.2.5.4 Operational Pointing Direction of SATOPS antenna

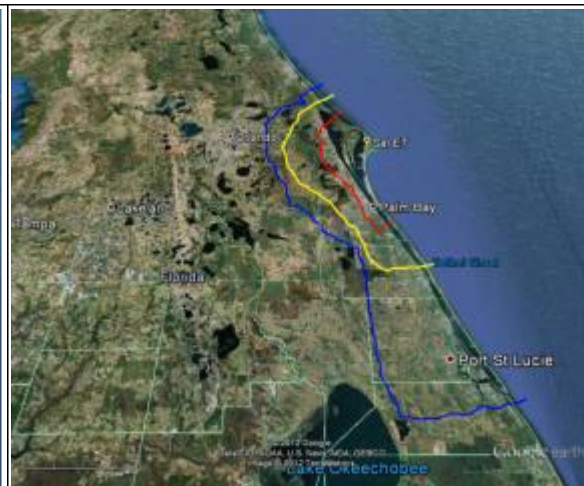
Due to normal operation of a SATOPS terminal there may exist a mission limit on the minimum elevation/azimuth angles the SATOPS antenna may use (particularly for geosynchronous orbit (GSO) spacecraft) and this would enhance the potential for sharing. Such mitigation is only feasible under the limitation that SATOPS operations are not being impeded. SATOPS at many sites do need full half hemisphere coverage based upon mission requirements. Operational factors that may apply for any given site will be based on the missions supported by the particular antennas at that site.

As an example consider the station located at Cape Canaveral Air Force Base (CCAFB)[35], due the proximity to the Cape Canaveral Launch facility the main mission of this antenna is likely to support launch operations. To analyze such an operational scenario it is assumed that the pointing direction is limited such that the azimuth is between 0 degrees (Due North) and 180 degrees (Due South) with easterly pointing azimuth directions allowed. Such type of operation may be representative of the operational characteristics during launch and early operation of a satellite system. The results are based on using the systems listed above for channel 1 with the satellite uplink station transmitting at maximum power at all times. Taking advantage of operational SATOPS pointing requirements should be considered on a site-by-site basis as part of coordination between the local licensee and the SATOPS site operator.

[35] It should be noted the operations at CCAFB may not be extensive and these results are not easily transferred to other sites.



Interference of 1 dB desense assuming SATOPS terminal is pointing at 3 degrees elevation (no satellite tracking). No Power Control.



Interference at or below 1 dB desense for 100% of the time. Yellow line is Opt 1 and red is Opt 2 base station mitigation using the BS receive antenna.

Figure 4.2.5-6. 1 dB Desense for EVCF, baseline scenario showing impact of limiting SATOPS pointing direction, All Channel 1 Satellites.

4.2.5.5 Limit Ranging operation of SATOPS channels

DoD instruction[36] provides guidance that ranging operations should occur at the payload frequencies. To the extent possible, operations are continuing to shift this service to payload frequencies. This could continue to reduce the amount of time that SATOPS channels are used and will increase the ability to share between BS and SATOPS operations. This mitigation technique is only applicable to satellite systems which have payload spectrum use outside the SGLS bands.

DoD indicates that ranging at payload bands is already maximally used during nominal operations. The main use of SATOPS in the 1755-1850 MHz band is for TT&C during launch, early orbit activities and anomaly resolution (LEO&A). LEO&A also includes support of low data rate research spacecraft, training, testing, support of spacecraft during the initial activation phase, and control of LEO spacecraft during their disposal reentry. It should be clearly noted that L-band is used on a regular basis for primary TT&C for certain legacy space programs, such as GPS. Also, this band is used for low data rate applications for research type spacecraft and for disposal operations associated with low earth orbit spacecraft. LEO&A SATOPS requires low frequency (L-band) support due to the requirement to support randomly oriented spacecraft through all weather conditions.

[36] DoD Instruction 3100.12, September 14, 2000, *www.dtic.mil/whs/directives/corres/pdf/310012p.pdf* (last visited November 5, 2010).

4.2.5.6 Dual Band

This is an effort the DoD is undertaking to have spacecraft be configured to be able to uplink in 1755-1850 MHz and 2025-2110 MHz. This capability is already implemented on a few space systems and some ground equipment, but total implementation is very uncertain and problematic as to when, if ever, it will be completed. If and when this is accomplished, future growth and LTE sharing can be more easily accommodated by flexible DoD operational use of either band. Currently, none of the Government spacecraft to date can change their frequencies on orbit, although such equipment could be installed in the future. Therefore all of the current spacecraft that do not have this capability will need to continue to be supported in 1755-1850 MHz for up to 30 or more years depending on the specific spacecraft.

4.2.5.7 Offloading / Scheduling

Although, theoretically SATOPS interference to LTE could be reduced by optimally scheduling spacecraft supports across SATOPS sites, opportunities in this regard are very limited because both government and LTE systems have requirements to operate in an unscheduled manner 24/7. Due to the heavy loading of SATOPS sites, particularly AFSCN and specific needs of the various space systems, only very minimal offloading of scheduled contacts could be shifted between sites.

4.2.5.8 Multiple Input Multiple Output (MIMO)

MIMO antenna technology is included in the current release of LTE, and future releases will improve on the MIMO features implemented. This technology can improve the rate of the system via spatial multiplexing, increasing the quality of service for UEs, potentially even in the presence of interference from SATOPS. MIMO can also provide antenna diversity. This antenna diversity can improve robustness to interference on par with the product of the number of antennas employed by both the base station and the UE. For example, a base station with two antenna elements receiving from a UE that also has two antenna elements could improve tolerance to interference by approximately a factor of four. Note that the same antennas in a MIMO system cannot be used to provide both spatial multiplexing and antenna diversity at the same time. Implementations of MIMO with more antenna elements could allow for increased interference tolerance in combination with improvements in rate via spatial multiplexing. Optimal use of MIMO accounting for SATOPS interference would require additional implementation effort beyond what is currently included in the LTE standard.

Multi-User MIMO (MU-MIMO) is a variant of MIMO planned for future releases of LTE that would allow spatial multiplexing of multiple UEs by a single base station, and may eventually even allow for spatial multiplexing across multiple base stations. More advanced deployments of MU-MIMO could possibly account for an interfering SATOPS transmitter in the context of spatial multiplexing. Implementation would be significantly more complex and require further study, but could theoretically provide greater performance improvements than diversity approaches alone.

4.2.5.9 Reduced SATOPS Antenna Side lobes

Reducing the antenna side lobe levels of SATOPS terminals can directly reduce the interference level a LTE base station may receive by perhaps 10-30 dB, depending on the sophistication of the techniques employed. In most cases, this would be a major effort that probably would require replacement of the SATOPS antenna systems.

4.2.5.10 Selection of SATOPS Transmission Channels

Some DoD satellites have the capability to operate only on a single frequency and a few satellites have the capability of supporting two frequencies. For the satellites that have the capability to operate on multiple channels, some operations could be shifted to channels that do not impact commercial operations and could result in a reduction in the amount of time a base station receiver may receive interference. Since most SATOPS ground station must be capable of communicating with most satellite, this mitigation technique has only limited applicability to specific satellite systems which have the support for multiple SGLS channels. Even for these systems, each supported frequency may still interfere with LTE operations, requiring more complicated pre-planning for optimal SATOPS channel selection. As stated earlier, this technique has very limited utility since both Government and LTE operations are not known accurately ahead of time in many cases.

4.2.5.11 Selective Receiver RF Filtering

Front end selective filtering is a concept where the LTE base station will implement a tunable notch filter to significantly reduce the signal level from the SATOPS uplink station (by approximately tens of dB). This is a proven technique that can help to avoid receiver saturation and enhance the performance of time/frequency sharing techniques.

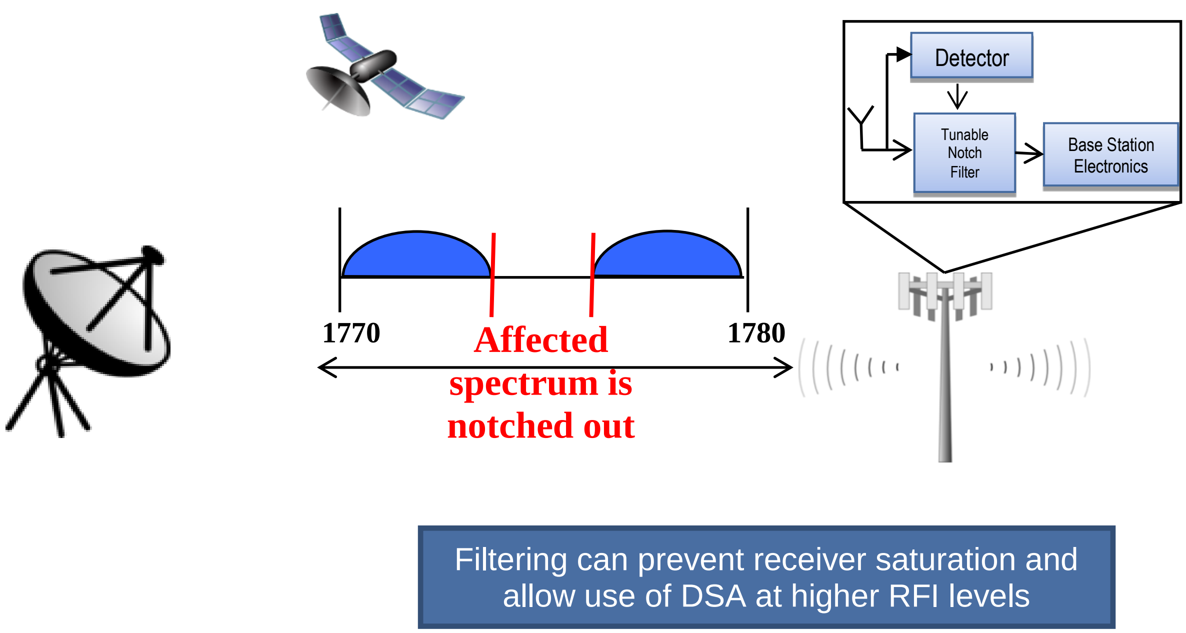


Figure 4.2.5-7. Front end selective filtering to avoid receive saturation.

4.2.5.12 Self Optimizing Networks

Cellular systems are in the process of using self organizing and self optimizing network tools that optimize LTE architectures in an adaptive manner. Further evaluation should consider how these techniques can be used to manage and improve operation in a dynamic fashion around the SATOPS sites.

4.2.5.13 Spectrum Efficient Waveforms

Classical communications theory indicates that AFSCN SATOPS emission bandwidth can be reduced by up to a factor of 8 and required power reduced as much as 18 dB with the use of new modulation (such as QPSK, 8PSK, 16-ary or higher order) and coding formats (such as Low Density Parity Check codes). These techniques would require new spacecraft and ground equipment. This would require up to 30 or more years to fully implement on all spacecraft. Note for comparison, that the implementation of new digital waveforms (see section 4.2.5.1) on the ground uses the existing modulation and coding, and can be done without modification of spacecraft equipment.

4.2.5.14 Spectrum Landscaping / Shielding

Shielding of antennas could significantly attenuate (10-50 dB or more depending on complexity) interfering signals arriving at a base station receiver and would enhance the opportunity for SATOPS sharing with LTE systems. Shielding can include natural features e.g., trees, bushes, hills as well as man-made structures. Shielding can be installed at the SATOPS site or at the base station site to provide the additional attenuation. In addition, placement of individual base stations can be selected to take advantage of natural shielding in the surrounding area, such as trees or buildings in the direction of the SATOPS site. It should be clearly noted that this may be a very attractive technique because the locations of the SATOPS and base station sites are fixed and known and thus shielding techniques could be tailored to the particular desired architecture. The amount of attenuation that can be obtained can be quite considerable and is been the subject of various studies[37]. Also, in many circumstances, the cost and other limiting factors could be quite low. Installation of shielding could potentially impact Government and/or LTE operations by obstructing desirable coverage areas. This tradeoff must clearly be considered in engineering the specific shielding solutions. Figure 4.2.5-10 illustrates one example showing the tradeoff between achieved attenuation of an interfering signal (arriving at 0 degrees) vs. attenuation of desired signals in a broader coverage area (+/- 50 degrees) due to the placement of a 10 foot square attenuating screen .

[37] Goldhirsh, Julius, Wolfhard J Vogel "Handbook of Propagation Effects for Vehicular and Mobile Satellite Systems" rev 3 Jan 2001

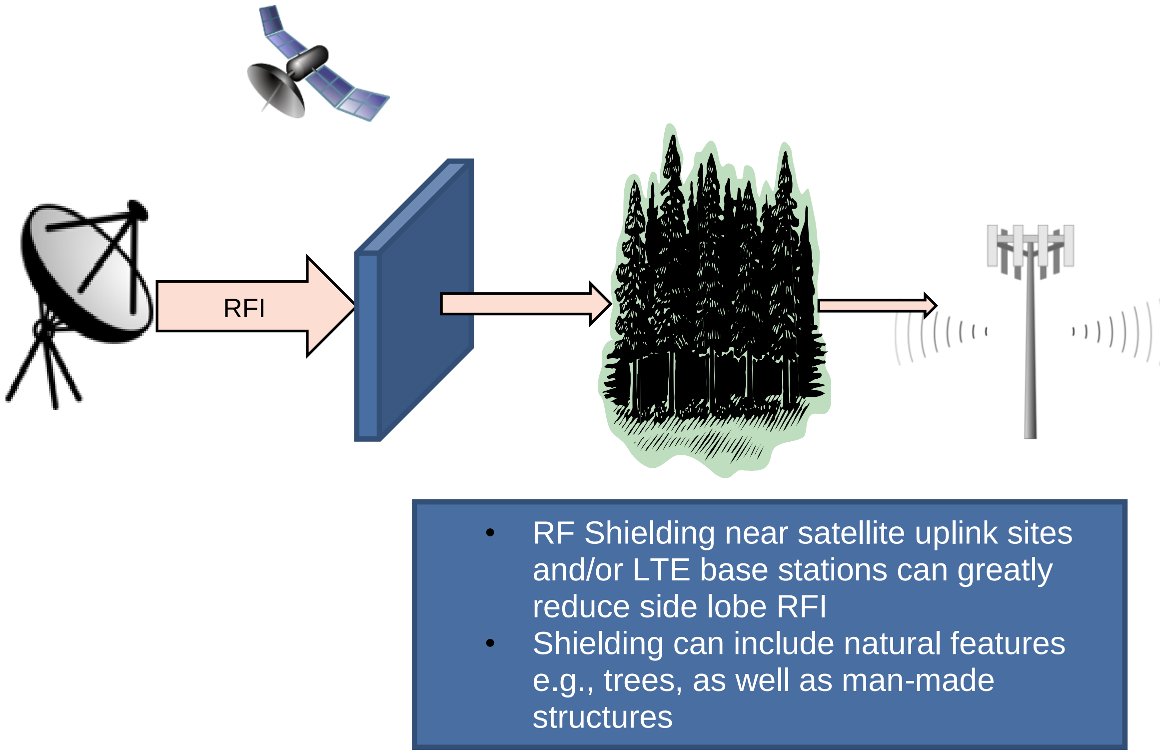


Figure 4.2.5-8. Shielding of interference from man-made and natural structures.

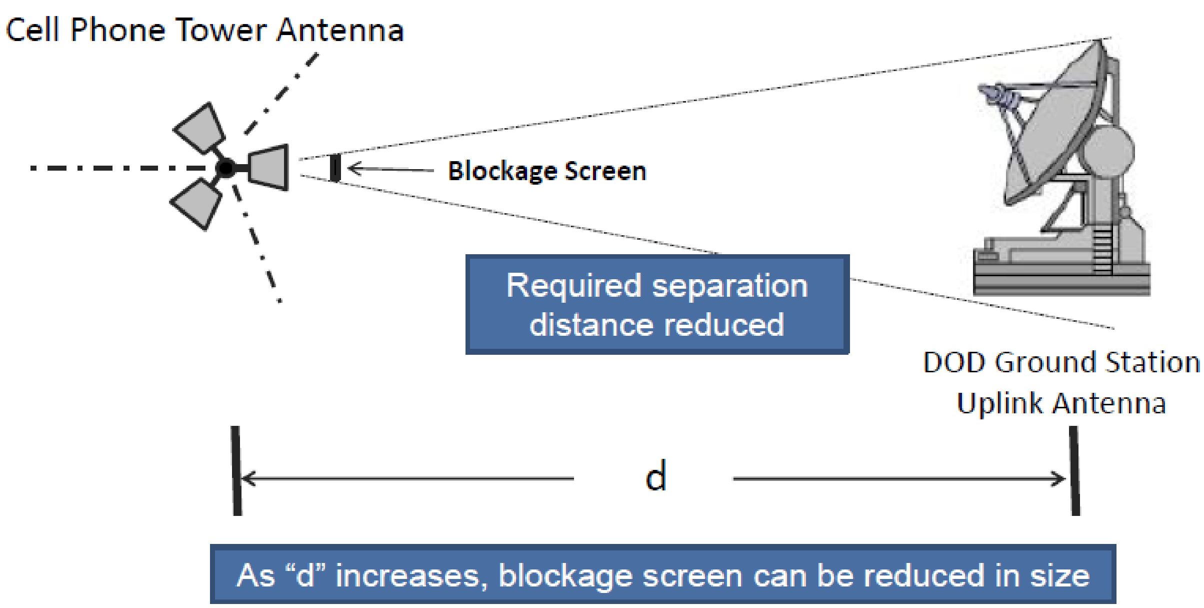


Figure 4.2.5-9. Representation of screen at the base station blocking reception of DOD Ground link operations.

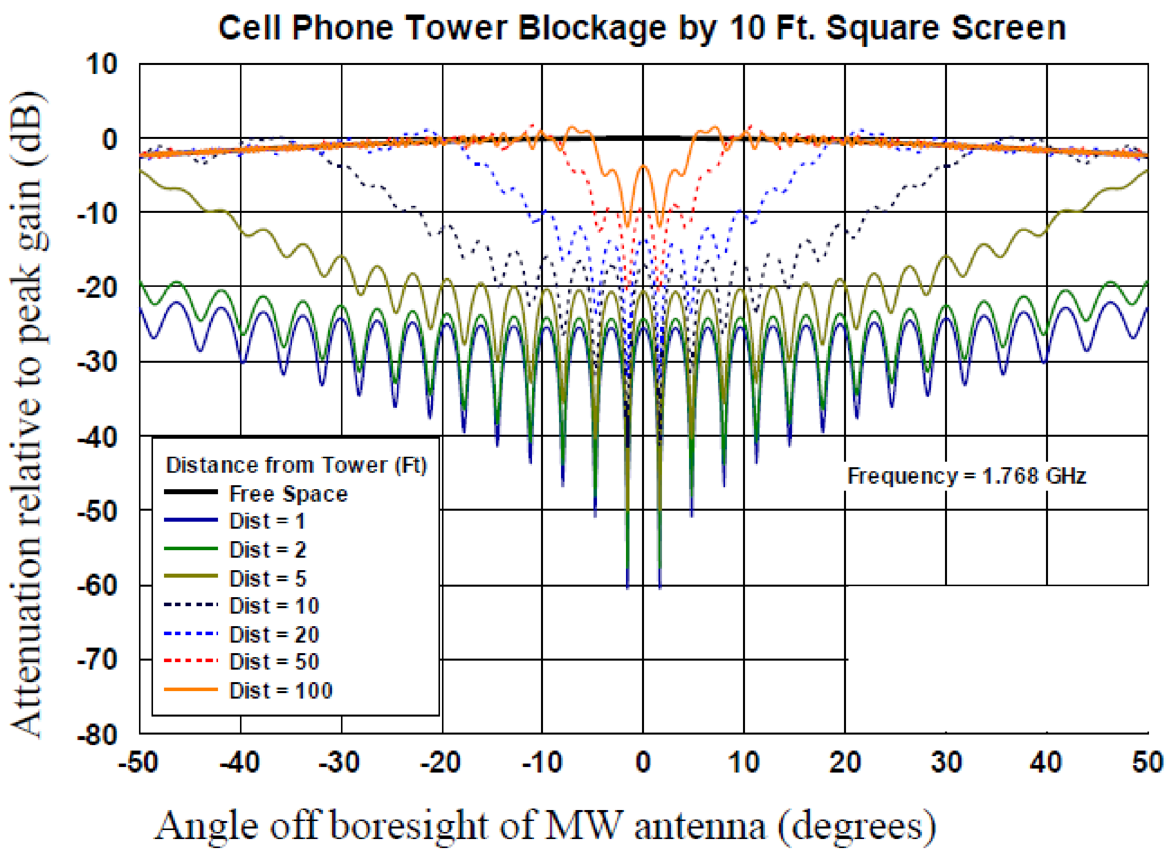


Figure 4.2.5-10. Estimate of attenuation by a 10 ft square screen.

4.2.5.15 Time/Frequency Sharing

Since SATOPS ground stations use a small number of channels in the 1755-1850 MHz band at any one time, time/frequency sharing may be possible. At any given moment, about 95% of the spectrum in the 1755-1850 MHz band will be free from SATOPS signal power, thus LTE base stations could theoretically schedule operations to minimize the impact of SATOPS interference. Current LTE equipment may not have the ability to schedule around SATOPS interference, but because LTE base stations currently schedule operations in time and frequency on the order of tens of milliseconds, future LTE equipment could support such a capability. This mitigation is only effective if the base station front end is not saturated by the interfering SATOPS signal, and thus may not be useful in locations very close to the SATOPS site, but may significantly improve performance in other regions. Cost factors include development of software for LTE scheduling in the presence of SATOPS interference as well as implementation of a means to detect the SATOPS interference.

The sensitive nature of SATOPS operations limits the practicality of providing advance notice of the SATOPS schedule to LTE operators, but the SATOPS signal detection by the LTE base station in real-time is expected to be feasible given the high power and known signal structure of the SATOPS emissions. Implementation may be assisted by cooperative testing with SATOPS sites. One implementation option would be the placement of LTE receivers tuned to listen for operations of SATOPS transmitters. If the locations receive a signal level above a certain threshold, the base station and/or system operator would be notified that SATOPS operations are occurring and would execute options to mitigate interference (e.g., shift users to other bands or other means).

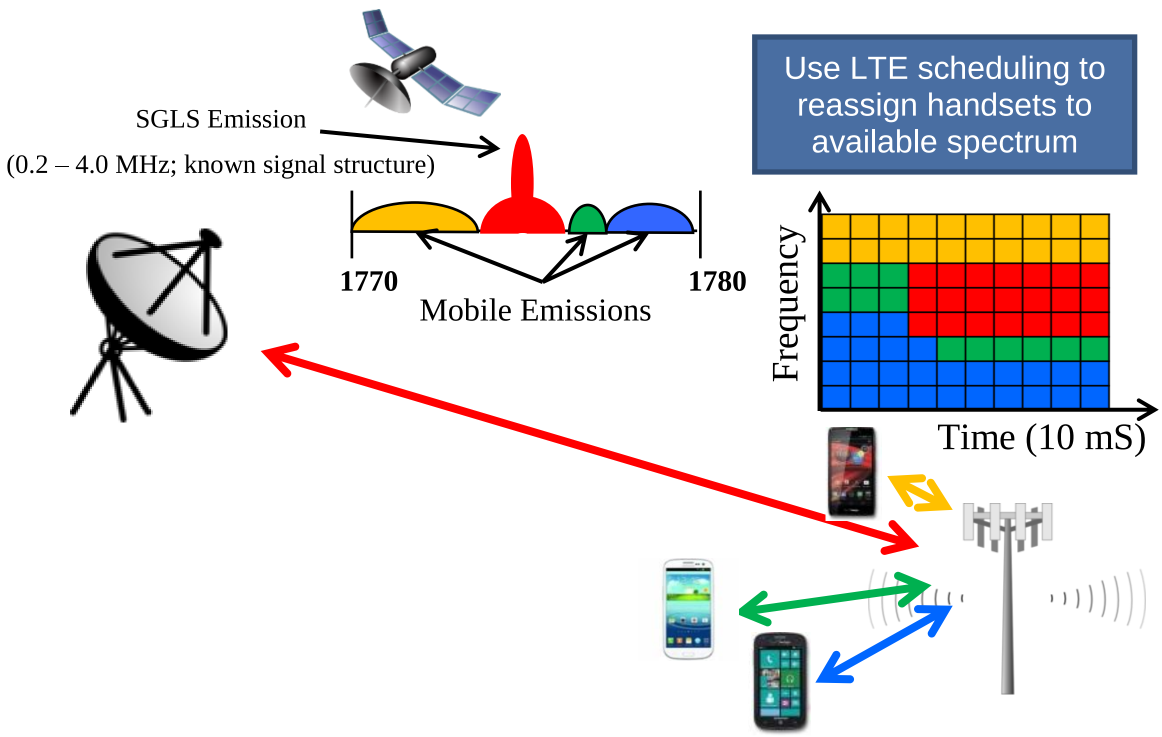


Figure 4.2.5-11. LTE Scheduling of spectrum resources to avoid use of channel in use by SATOPS station.

4.2.5.16 Uplink Power Control

Use of power control on SATOPS ground stations may allow for some improvement in sharing with LTE systems. This technique will not apply to situations where the communications with a satellite is at risk or under anomaly conditions. Under such operations the SATOPS uplink station will operate at maximum power to ensure communications. Anomaly operation is not the normal condition and occurs approximately <1% of the time. It is not possible to predict when such anomaly conditions will occur and the duration of such conditions. Also, typically, Government mission requirements are set to provide assured access. This is fundamental to military operations because critical national security needs can change very quickly. Therefore such uplink power control could cause an unacceptable risk to satellite health and safety, if the power is too low to ensure communication with the satellite. Reduced SATOPS uplink power increases the risk of not being able to contact and command the satellite successfully. This could potentially cause damage to the satellite or result in loss of the satellite. The Government must take much more care in the avoidance of mission degradation because, in many cases, that would be a safety-of-life issue.

Shown below in Table 4.2.5-2 is a bounding link budget for the USKW satellite communicating with NHS showing the range of power from the maximum feasible at the NHS site to the minimum to close the link with a small margin. As indicated, the link has over 46 dB of margin relative when the satellite is at minimum elevation. Note that the USKW example shown is not typical of SATOPS operational cases in practice, but is shown for illustrative purposes. Under anomaly operations the satellite receive gain may be 16 dB lower due to the possibility of a tumbling satellite. Also shown in the table is a link budget for a GSO satellite, USGAE-10. As indicated communications with this satellite will not have as much link margin and is illustrative that the ability of this technique to reduce interference to the LTE base station has limitations. As seen it is highly dependent upon the mission and current state of the spacecraft that is being commanded by the SATOPS terminal. Note also that reduction in uplink power may increase the susceptibility of SATOPS space-borne receivers to aggregate interference from LTE operations (see section 4.2.6).

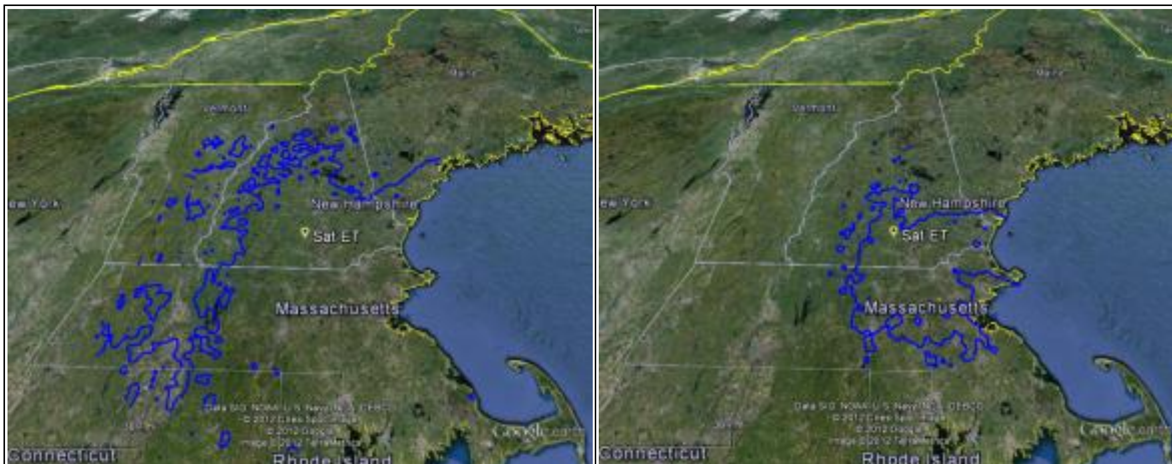
Table 4.2.5-2: Link budget for USKW and USGAE-10 satellite showing impact of power control.

SATOPS Parameters	**USKW**		**USGAE-10**	
	Max Power	Min Power	Max Power	Min Power
Tx Frequency (MHz)	1762	1762	1812	1812
Tx Power (dBm)	68.6	23.66	68.6	65.03
Peak Antenna Gain (dBi)	45	45	45	45
Peak EIRP (dBm)	113.6	68.66	113.60	110.03
Satellite Altitude (km)	630	630	35768	35768
Minimum Elevation (deg)	3	3	-	-
Distance from SGLS station to Satellite at minimum elevation (km)	2589.3	2589.3	41702.79	41702.79
Free Space Loss (dB)	165.64	165.64	190.02	190.02
Satellite Rx Gain (dBi)	6	6	-4	-4
Noise Bandwidth (MHz)	4.004	4.004	2.9	2.9
Noise Temperature (K)	288	288	630	630
Required C/N (dB)	15	15	20	20
C/N (dB)	61.95	17.00	25.57	22.00
Margin (dB)	46.95	2.00	5.57	2.00

Shown in Figure 4.2.5-12 to Figure 4.2.5-15 are the comparison of operations for channel 1 with maximum power at minimum elevation angle with the SATOPS terminal tracking the satellite with the lowest elevation angle and using power control. The satellite characteristics are those found in Table 4.2.3-16. These figures were computed for a grid of base stations with 5 km spacing and distributed with-in 150 km of the SATOPS uplink terminal. The computation assumed that the transmit power is set such that the C/N at the satellite has 2 dB of margin above the minimum C/N required for communication. For the satellite systems listed to operate in channel 1, the 2 dB margin level will result in a power reduction of 28-43 dB.

Interference of 1 dB desense assuming SATOPS terminal is pointing at 3 degrees elevation (no satellite tracking). No Power Control.	Interference at or below 1 dB desense for 100% of the time. Power Control to C/N of 17 dB.

Figure 4.2.5-12. 1 dB Desense for HTS, baseline scenario showing no power control and power control to 17 dB C/N, all Channel 1 Satellites are considered.



Interference of 1 dB desense assuming SATOPS terminal is pointing at 3 degrees elevation (no satellite tracking). No Power Control.	Interference at or below 1 dB desense for 100% of the time. Power Control to C/N of 17 dB.

Figure 4.2.5-13. 1 dB Desense for NHS, baseline scenario showing no power control and power control to 17 dB C/N, all Channel 1 Satellites are considered.

Interference of 1 dB desense assuming SATOPS terminal is pointing at 3 degrees elevation (no satellite tracking). No Power Control.	Interference at or below 1 dB desense for 100% of the time. Power Control to C/N of 17 dB.

Figure 4.2.5-14. 1 dB Desense for VTS, baseline scenario showing no power control and power control to 17 dB C/N, all Channel 1 Satellites are considered.

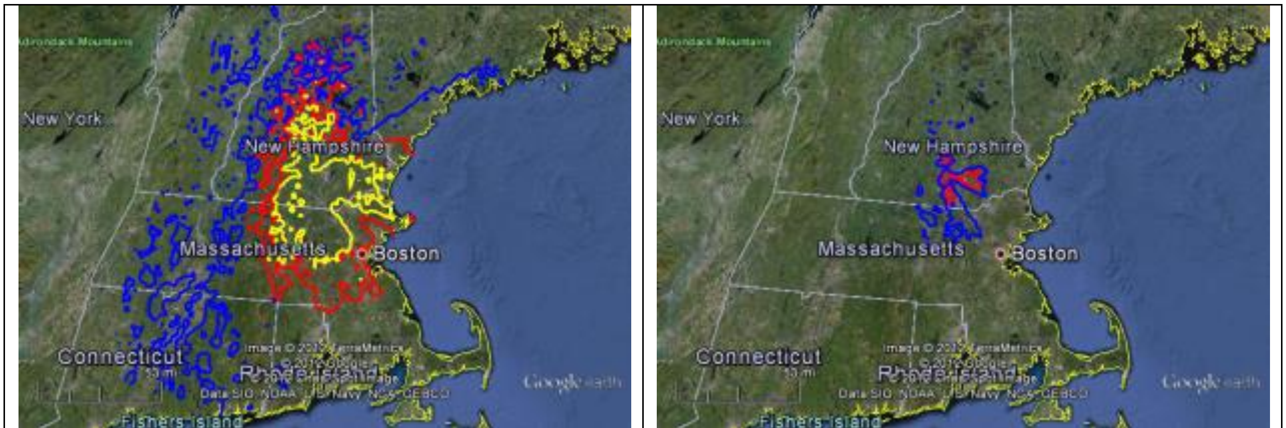
Interference of 1 dB desense assuming SATOPS terminal is pointing at 3 degrees elevation (no satellite tracking). No Power Control.	Interference at or below 1 dB desense for 100% of the time. Power Control to C/N of 17 dB.

Figure 4.2.5-15. 1 dB Desense for GTS, baseline scenario showing no power control and power control to 17 dB C/N, all Channel 1 Satellites are considered.

4.2.5.17 Summary

A survey of available techniques, analysis, and simulation results indicate that interference can be significantly reduced by the application of various mitigation methods. While techniques do vary in their effectiveness, no particular techniques are recommended or discouraged. All techniques should continue to be evaluated and considered for use in the context of ongoing improvement of sharing between SATOPS and LTE operations.

Figure 4.2.5-16 illustrates the impact of mitigation on the reduction of the size of the zone for a 1 dB desense. The 0 dB mitigation is based on the zone expected when the satellite uplink terminal is operating at its maximum power and pointed at 3 degrees elevation in all directions around the earth terminal location. The figure on the right shows the effect of the dimensions of zone due to 40-60 dB mitigation. This clearly demonstrates the possible increase in area available for effective LTE operations.



Amount of Mitigation: Blue = 0 dB, Red = 20 dB, Yellow = 40 dB	Amount of Mitigation: Blue = 60 dB, Red = 80 dB

Figure 4.2.5-16. Reduction in desense zone around NHS site based on amount of mitigation implemented, 0 dB is full power operations at minimum elevation angle for uplink site.

4.2.6 Analysis of LTE Interference to Space-Borne Satellites

4.2.6.1 Introduction

A key aspect of assessing the feasibility between LTE and Federal SATOPS systems in the 1761-1842 MHz band is the question of whether the aggregate interference resulting from all LTE operations will cause harmful interference to SATOPS receivers on Federal spacecraft. Figure 4.2.6-1 illustrates this problem. This section presents analysis and results for predicting aggregate RFI to SATOPS receivers that would result from commercial LTE network operations in the 1755-1850 MHz band, in this case the aggregate emission from all transmitting mobile devices is computed. Low risk of harmful interference from aggregate LTE to SATOPS is predicted based on current assumptions, however, establishment of regulations to ensure continued protection of satellite receivers is recommended

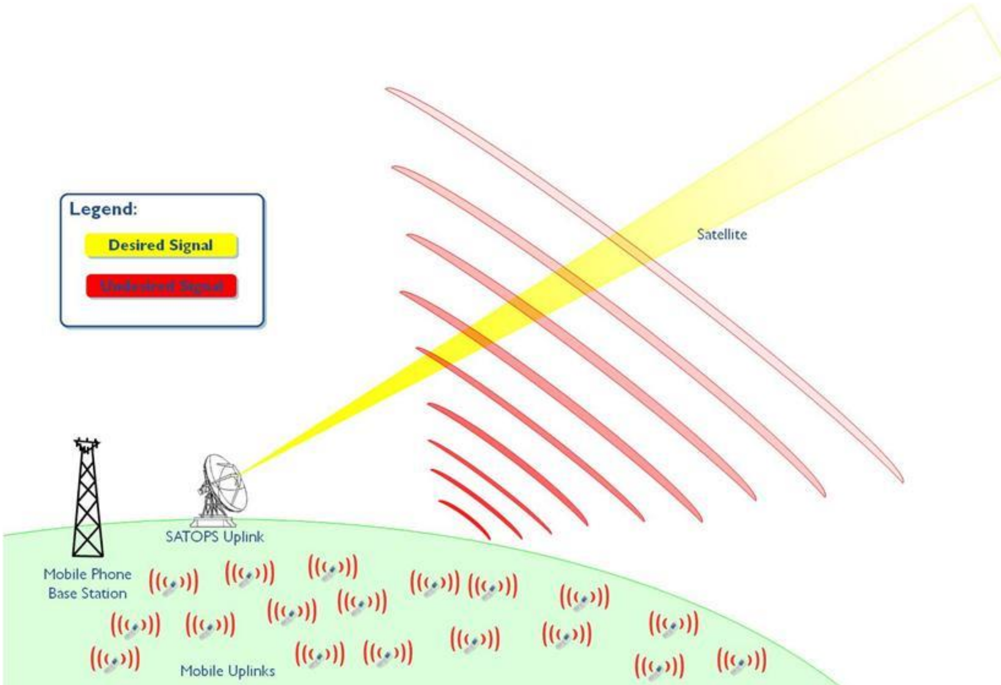


Figure 4.2.6-1. Aggregate LTE Interference to SATOPS Receivers

4.2.6.2 LTE Aggregate Interference Model

To evaluate aggregate LTE interference to Federal SATOPS receivers in 1761-1842 MHz, DoD created a model to represent UEs distributed across the U.S. and compute the resulting total interference power at DoD spacecraft. Only UE transmitters were examined in this analysis based on the assumption that 1755-1850 MHz would be used for LTE uplinks, and that base station transmissions would be accomplished at another frequency. The same model can be used to examine interference due to base station transmissions if expectations for LTE change in the future.

The model is run for each DoD program and accounts for the parameters of that program, as well as parameters that describe the LTE network. LTE parameter inputs to the model are based on the CSMAC WG1 Final Report[38]. Key inputs to the model include:

- Spacecraft sensitivity - the threshold interference power density incident at the spacecraft antenna that would be considered harmful. This sensitivity is computed for each program based on link requirements contained in relevant interface documentation. The threshold represents the amount of additive thermal noise power that would result in failure to meet the link closure requirement.

[38]"Commerce Spectrum Management Advisory Committee Final Report Working Group 1 – 1695-1710 MHz Meteorological-Satellite" January 22, 2013

- Spacecraft position – the location of the Federal satellite in space. This input is handled parametrically. Only spacecraft altitude is entered into the model. Interference power is then computed for all possible locations of the spacecraft at that altitude and the highest interference value is identified.
- LTE antenna gain - the nominal gain of all LTE transmitters towards the spacecraft. UEs are assumed to have an omni-directional antenna pattern.
- UEs/Base Station – the number of UEs that are transmitting in the area served by a single base station. The value provided by CSMAC WG 1 of 18 UEs/Base Station is understood to represent the number of simultaneously transmitting UEs per base station in a 10 MHz bandwidth network. (See Section 4.2.1)
- LTE channel bandwidth - the assumed channel bandwidth of the LTE network. For the purposes of this analysis, a 10 MHz LTE network is assumed to completely overlap the bandwidth of the Federal SATOPS receiver in the 1755-1850 MHz band. (See Section 4.2.1)
- Rural/Urban cell radius - the coverage area of each individual base station. This value is used to determine how many base stations (and thus how many UEs) are operating in a given land area. Note that cell radii take on one of two values depending on whether the base station is in an area considered to be urban or rural. The radius values used in the model are half the inter-site distances identified in the CSMAC WG 1 report. (See Section 4.2.1.2)
- Rural/Urban UE power - the mean transmitter power of UEs, depending on whether the UE is in a rural or suburban area. Values used in the model are based on power distribution statistics for the UE provided in the CSMAC WG 1 report. (See Section 4.2.1.2)
- Rural/Urban UE variance - a statistical metric for the variation of UE transmitter power due to power control of the UE. Both the mean and variance terms are derived from UE transmit power distributions provided by CSMAC WG 1. (See Section 4.2.1.2)

The modeling method for the distribution of LTE systems across the U.S. was recommended by CSMAC WG 1. It identifies a list of the top 100 cities in the U.S. in terms of most desired LTE market areas. A map of these market areas is shown in Figure 4.2.6-2. LTE systems operating with suburban parameters (defined by CSMAC WG 1) are placed in a circular land area with 30 km radius at each of these cities. In addition, LTE systems operating with rural parameters are placed in a ring of land area with 30 km inner radius and 100 km outer radius around the suburban circle. No LTE systems are assumed to operate outside of these 100 cities. With this approach and the input parameters described above, the resulting 10 MHz LTE network consists of approximately 170,000 base stations and 3 million simultaneously transmitting UEs across the US[39]. Note that only a fraction of these UEs would effectively impact any given SATOPS receiver since the SATOPS bandwidth is only a fraction of the 10 MHz LTE network bandwidth, and out-of-band interference effects were not considered in this analysis.

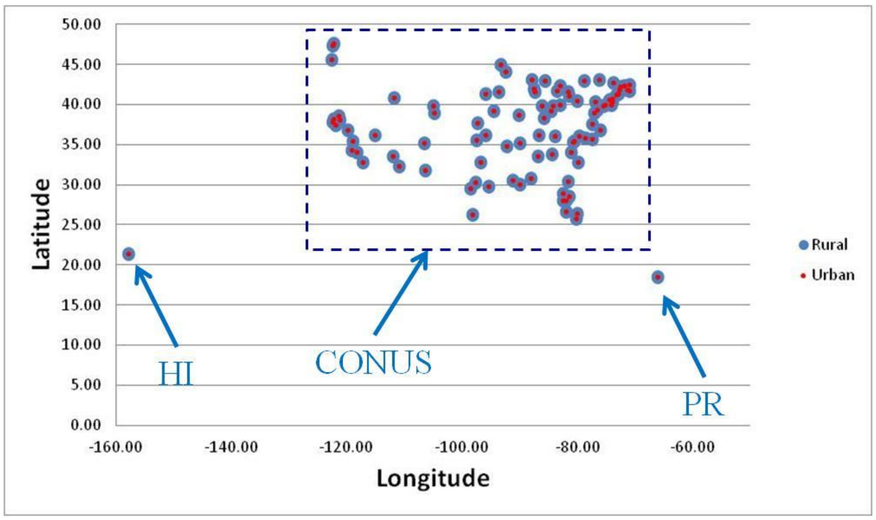


Figure 4.2.6-2. Modeled LTE Market Areas

With the LTE network distribution modeled across the U.S., interference is calculated for each market area that has a positive elevation angle to the victim satellite location using typical link analysis. Total market area transmit power is assumed to be the sum of all transmitter powers in the market area. The resulting market area transmit power is assumed to have a flat/constant power spectral density across the 10 MHz bandwidth. The propagation path is assumed to be from the center of the urban area circle to the satellite location. Free space path loss is assumed and the SATOPS receiver is assumed to have a constant antenna gain towards all interference sources. Atmospheric loss is included but amounts to less than a tenth of a dB at this frequency range. Total interference at the spacecraft is determined by summing power contributions from each market area. The uncorrelated nature and large number of individual transmitters makes

[39] Note the number of base stations and simultaneously transmitting UEs originally presented in the federal submittal in section 4.4.3 are not consistent with the values presented here due to a typographical error in section 4.4.3. Also note that the correct number of UEs was used in the analysis and is accurately reflected in the result both here and in section 4.4.3.

power summing appropriate. It is assumed that total resulting interference power can be well approximated as a flat increase in thermal noise across the band. In this way, the estimated aggregate interference power density can be compared directly against a SATOPS interference power density threshold without having to explicitly account for individual SATOPS mission bandwidths.

The standard deviation of the aggregate interference is also computed based on the variance of the power distribution for individual UEs. This allows for an evaluation of whether the aggregate interference should be expected to fluctuate significantly over time due to UE power control. The computation is straightforward using the basic property that the variance of a sum of random variables multiplied by some constants is equivalent to the sum of the square of the constants multiplied by the variance of the individual random variables. Thus the variance of the aggregate interference, which is the sum of all the UE transmit powers multiplied by appropriate link parameters, is equivalent to the sum of the square of the link parameters multiplied by the individual UE transmitter variance.

4.2.6.3 LTE Aggregate Interference Analysis Results

Modeling was conducted for most relevant major Air Force, Navy, and NOAA SATOPS space programs. An interference power density threshold at the satellite receiver was computed for each program based on relevant requirements and interface documentation. Interference thresholds for all programs were then used to determine a single threshold that would protect all programs from harmful interference. An interference level of -205 dBW/Hz into a SATOPS receiver, assuming a 0 dBi antenna and no other losses, (equivalent to a power flux density of -179 dBW/Hz/m^2) was determined to be a safe interference level at geostationary orbit for most programs. Note that while this threshold is referenced to a geostationary orbit, it effectively protects programs in non-geostationary orbit as well. This can be conceptually explained recognizing that the differences in distance between the SATOPS site and the interference sources to the spacecraft are approximately equal regardless of the spacecraft’s altitude. This means a carrier to interference plus noise ratio, which is a useful metric for evaluating the severity of interference, is insensitive to the orbit of the spacecraft. Also note that while the threshold is presented her on a per Hz basis, this can be readily translated to other reference bandwidths with the assumption that aggregate LTE emissions will have an approximately constant power spectral density across their band of operations. For example, the -205 dBW/Hz threshold can also be stated as a -175 dBW/kHz or -145 dBW/MHz threshold.

The model was used to calculate the interference power density present at the geostationary orbit due to the LTE network for the worst-case point in the spacecraft’s orbit and using the LTE parameter and deployment assumptions described above. The resulting estimated interference power density is -212.6 dBW/Hz. Comparing this to the aforementioned -205 dBW/Hz threshold, there is 7.6 dB of positive margin. Figure 4.2.6-3 plots the interference power density estimated for all longitudes in the geostationary orbit.

The -205 dBW/Hz threshold is not sufficient to protect a few experimental programs which have much more conservative requirements than most programs. It is not conclusive that these programs will or won’t receive harmful interference from the planned LTE network. Additional consideration for these programs, and possible future programs that may have similar requirements, may be required during the development of transition plans. Transition planning is expected to follow after the CSMAC WGs complete their recommendations.

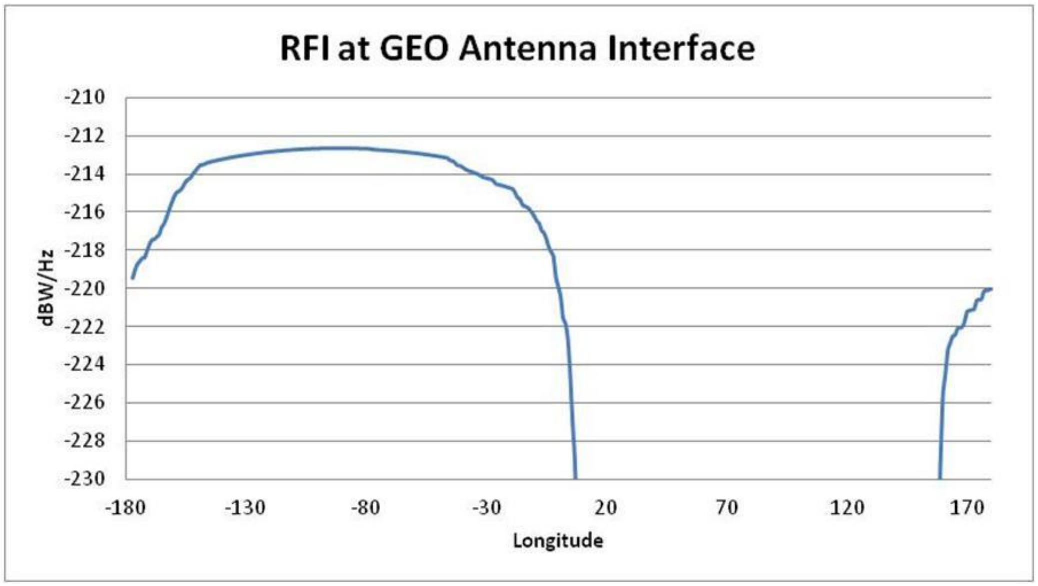


Figure 4.2.6-3. Estimated interference power density at geostationary orbit

The analysis and modeling use some assumptions which are expected to over-estimate the level of interference. One of the most significant of those is that the modeling assumes all UEs have direct line of site to the satellite. In practice, UEs are used in buildings, in cars, near trees etc. Transmitting through a window or a wall from inside a building adds significant attenuation. Other assumptions that may over-estimate interference include representation of the network during peak demand with a very large deployment of approximately 170,000 base stations. Due to these assumptions, practical interference from LTE deployment in the U.S. is expected to be significantly less than that predicted by the model. Furthermore, we recognize that the program requirements used to identify the interference threshold are often based on the most stressing cases anticipated for the spacecraft, indicating that spacecraft may be more tolerant of interference during nominal operations.

Consideration of emissions from U.S. systems is anticipated to under-estimate aggregate interference to SATOPS receivers, since other countries may deploy networks in the band and will be visible to U.S. satellites, use and will continue to be use the band for fixed and mobile services internationally. The field-of-view of a SATOPS receiver in geostationary orbit covers almost an entire hemisphere as shown in Figure 4.2.6-4. Thus mobile wireless deployments in Central America, South America, Western Europe, and East Asia could also contribute to aggregate interference levels depending on the specific satellite locations. While systems outside of the U.S. were considered to be beyond the scope of the WG 3 effort, the effects of such systems should be considered in on-going SATOPS-LTE band sharing processes.

Figure 4.2.6-4. Field of View of a Geostationary Satellite at 102 Degrees West Longitude.

Modeling and analysis is based on LTE parameters from CSMAC WG 1 and SATOPS receiver parameters from a large representative set of national security space programs. The analysis results and modeling are highly dependent on the parameters assumed for the LTE systems. The CSMAC WG 1 parameters are assumed to represent the commercial industry's best approximation of how LTE systems would operate in this band. However, commercial LTE technology changes rapidly relative to the long life cycles of national security spacecraft. Possible changes to LTE parameters due to evolving technology could conceivably result in eventual harmful interference to SATOPS systems. For this reason, a regulatory mechanism to prevent such an outcome is recommended. Specifically, NTIA and FCC should develop a process to estimate the projected interference resulting from licensees. If it is estimated that aggregate interference from LTE will exceed the -205 dBW/Hz threshold, the FCC and the licensees will modify operations, deployment plans, and/or regulations as needed to ensure that LTE deployments do not cause harmful interference to Federal spacecraft. The threshold and projection process should be included in national regulations, transition plans, and in the language of the auction winner's license to ensure enforceability.

4.2.6.4 Aggregate Interference Analysis Summary and Conclusions

Analysis under current assumptions indicates that aggregate LTE interference to SATOPS spacecraft receivers will not be harmful. A basic methodology for estimating the interference, drawing heavily from CSMAC WG 1 description of LTE parameters, was described. With this methodology, an interference power density of -212.6 dBW/Hz at geostationary orbit was predicted and compared to an interference threshold for SATOPS of -205 dBW/Hz, resulting in an approximately 7.6 dB positive margin. However, recognizing that mobile technologies evolve rapidly relative to long SATOPS lifecycles, a regulatory mechanism is needed to project estimated interference levels. Specifically, FCC should include in their rulemaking a process for a technical showing of compatibility between mobile licensees and SATOPS uplinks. Specifically, it should be shown that aggregate interference levels from licensees are not projected to exceed a threshold of -205 dBW/Hz interference power density into a reference antenna of 0 dBi (equivalent to -178.5 dBW/Hz/m^2 power flux density at 1800 MHz), measured at geostationary orbit. This technical showing should be provided no later than 2 years after the issuance of initial licenses and should provide a projection based on deployment 5 years into the future. The showing should also be updated periodically, where an appropriate period should be determined by FCC that captures significant changes in deployment strategies and technology without excessive analytical burden. Note that the technical information provided by individual licensees is anticipated to be proprietary and thus the overall determination of compatibility, accounting for all licensee inputs, will need to be determined by the FCC. If aggregate interference is ever projected or otherwise found to exceed the threshold, FCC and the mobile licensees will modify operations and deployment plans appropriately to protect SATOPS receivers from harmful interference.

Recommendation 4.2.6-1: CSMAC recommends that the FCC propose in their rulemaking a requirement on licensees which overlap any of the 1761-1842 MHz band that specifies a technical showing of compatibility with satellite uplinks.

- The aggregate for all licensees on the same frequency is a compliance level, in terms of power flux density at the geostationary orbit (GSO), not to exceed -179 dBW/Hz/m^2 .
- The initial showing shall be provided no later than 2 years after the issuance of the license and must contain technical data supporting the current deployment and an projected estimate of the deployment for 5 years in the future.
- The showing shall be updated on a periodic basis to be determined by the FCC.
- Due to the nature of such a showing, all data shall be proprietary between the licensee, FCC and NTIA (including government earth station operators).

Recommendation 4.2.6-2: CSMAC recommends the FCC consider in its rulemaking methods to ensure that the following conditions be met to ensure the aggregate commercial wireless mobile broadband emissions will not exceed the acceptable threshold power level, including:

- Method to aggregate the individual showings into a single value expected at the GSO arc from all licensees.
- The actions to be taken by the FCC to reduce the projected aggregate emissions if it is projected to exceed the threshold.
- The actions to be taken by the FCC to eliminate harmful interference if it does occur, to include potential cessation of operations by the commercial licensee(s) on the affected frequency until interference is resolved.

Recommendation 4.2.6-3: CSMAC recommends the NTIA investigate measures that can be implemented in its NTIA manual to enhance future spectrum sharing with mobile broadband